Guide to the Slit Spectra Reduction Task DOECSLIT

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ABSTRACT

Doecslit subtracts background sky or scattered light, extracts, wavelength calibrates, and flux calibrates multiorder echelle slit spectra which have been processed to remove the detector characteristics; i.e. CCD images have been bias, dark count, and flat field corrected. The spectra should be oriented such that pixels of constant wavelength are aligned with the image columns or lines. Small departures from this alignment are not critical resulting in only a small loss of resolution. Single order observations should be reduced with **doslit**.

1. Introduction

Doecslit subtracts background sky or scattered light, extracts, wavelength calibrates, and flux calibrates multiorder echelle slit spectra which have been processed to remove the detector characteristics; i.e. CCD images have been bias, dark count, and flat field corrected. The spectra should be oriented such that pixels of constant wavelength are aligned with the image columns or lines. Small departures from this alignment are not critical resulting in only a small loss of resolution. Single order observations should be reduced with **doslit**.

The task is a command language script which collects and combines the functions and parameters of many general purpose tasks to provide a single, complete data reduction path and a degree of guidance, automation, and record keeping. In the following description and in the parameter section the various general tasks used are identified. Further information about those tasks and their parameters may be found in their documentation. **Doecslit** also simplifies and consolidates parameters from those tasks and keeps track of previous processing to avoid duplications.

The general organization of the task is to do the interactive setup steps, such as the aperture definitions and reference dispersion function determination, first using representative calibration data and then perform the majority of the reductions automatically, possibly as a background process, with reference to the setup data. In addition, the task determines which setup and processing operations have been completed in previous executions of the task and, contingent on the `redo` and `update` options, skip or repeat some or all the steps.

The description is divided into a quick usage outline followed by details of the parameters and algorithms. The usage outline is provided as a checklist and a refresher for those familiar with this task and the component tasks. It presents only the default or recommended usage since there are many variations possible.

2. Usage Outline

[1] The images are first processed with **ccdproc** for overscan, zero level, dark count, and flat field corrections.

[2] Set the **doecslit** parameters with **eparam**. Specify the object images to be processed, an aperture reference image (usually a bright star spectrum) to use in finding the orders and defining the aperture parameters, one or more arc images, and one or more standard star images. If there are many object, arc, or standard star images you might prepare "@ files". Set the detector and data specific parameters. Select the processing options desired. Finally you might wish to review the **sparams** algorithm parameters though the defaults are probably adequate.

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[3] Run the task. This may be repeated multiple times with different observations and the task will generally only do the setup steps once and only process new images. Queries presented during the execution for various interactive operations may be answered with "yes", "no", "YES", or "NO". The lower case responses apply just to that query while the upper case responses apply to all further such queries during the current execution and no further queries of that type will be made.

[4] The specified number of orders (ranked by peak strength) in the aperture reference image are located and default fixed width apertures are assigned. If the resize option is set the apertures are resized by finding the level which is 5% (the default) of the peak above local background. You then have the option of entering the aperture editing loop to check the aperture positions, sizes, and background fitting parameters. This is highly recommended. Note that it is important that the aperture numbers be sequential with the orders and if any orders are skipped the aperture numbers should also skip. It is also important to verify the background regions with the 'b' key. Usually you want any changes made to the background definitions to apply to all apertures so use the 'a' key to select all apertures before modifying the background parameters. To exit the background mode and then to exit the review mode use 'q'.

[5] The order positions at a series of points along the dispersion are measured and a function is fit to these positions. This may be done interactively to examine the traced positions and adjust the fitting parameters. To exit the interactive fitting type 'q'. Not all orders need be examined and the "NO" response will quit the interactive fitting using the last defined fitting parameters on the remaining traces.

[6] Apertures are now defined for all standard and object images. This is only done if there are no previous aperture definitions for the image. The aperture references previously defined are used as the initial set of apertures for each image. The apertures are then recentered by an average shift over all orders and resized if that option is selected. The apertures may also be retraced and interactively examined for each image if the tracing option is selected and quicklook mode is not.

[7] If scattered light subtraction is selected the scattered light parameters are set using the aperture reference image and the task **apscatter**. The purpose of this is to interactively define the aperture buffer distance for the scattered light and the cross and parallel dispersion fitting parameters. The fitting parameters are taken from and recorded in the parameter sets **apscat1** and **apscat2**. All other scattered light subtractions are done noninteractively with these parameters. Note that the scattered light correction modifies the input images. Scattered light subtraction is not done in quicklook mode.

[8] If dispersion correction is selected the first arc in the arc list is extracted. The dispersion function is defined using the task **ecidentify**. Identify a few arc lines in a few orders with 'm' and 'o' and use the 'l' line list identification command to automatically add additional lines and fit the dispersion function. Check the quality of the dispersion function fit with 'f'. When satisfied exit with 'q'.

[9] If the flux calibration option is selected the standard star spectra are processed (if not done previously). The images are background subtracted, extracted, and wavelength calibrated. The appropriate arc calibration spectra are extracted and the dispersion function refit using the arc reference spectrum as a starting point. The standard star fluxes through the calibration bandpasses are compiled. You are queried for the name of the standard star calibration data file. Because echelle spectra are often at much higher dispersion than the calibration data interpolated bandpasses may be defined with the bandpass parameters in **sparams** and checked or modified interactively.

After all the standard stars are processed a sensitivity function is determined using the interactive task **sensfunc**. Finally, the standard star spectra are extinction corrected and flux calibrated using the derived sensitivity function.

[10] The object spectra are now automatically background subtracted (an alternative to scattered light subtraction), extracted, wavelength calibrated, and flux calibrated.

[11] The option to examine the final spectra with **splot** may be given. To exit type 'q'. In quicklook mode the spectra are plotted noninteractively with **specplot**.

[12] The final spectra will have the same name as the original 2D images with a ".ec" extension added.

3. Spectra and Data Files

The basic input consists of echelle slit object, standard star, and arc calibration spectra stored as IRAF images. The type of image format is defined by the environment parameter *imtype*. Only images with that extension will be processed and created. The raw CCD images must be processed to remove overscan, bias, dark count, and flat field effects. This is generally done using the **ccdred** package. Flat fields which are not contaminated by low counts between the apertures may be prepared with the task **apflatten** (recommended) or **apnormalize**. Lines of constant wavelength across the orders should be closely aligned with one of the image axes. Sometimes the orders are

aligned rather than the spectral features. This will result in a small amount of resolution loss but is often acceptable. In some cases one may correct for misalignment with the **rotate** task. More complex geometric problems and observations of extended objects should be handled by the **longslit** package and single order observations should be processed by **doslit**.

The aperture reference spectrum is generally a bright star. The arc spectra are comparison arc lamp observations (they must all be of the same type). The assignment of arc calibration exposures to object exposures is generally done by selecting the nearest in time and interpolating. However, the optional *arc assignment table* may be used to explicitly assign arc images to specific objects. The format of this file is described in task **refspectra**.

The final reduced spectra are recorded in two or three dimensional IRAF images. The images have the same name as the original images with an added ".ec" extension. Each line in the reduced image is a one dimensional spectrum with associated aperture, order, and wavelength information. When the `extras` parameter is set the lines in the third dimension contain additional information (see **apsum** for further details). These spectral formats are accepted by the one dimensional spectroscopy tasks such as the plotting tasks **splot** and **specplot**. The special task **scopy** may be used to extract specific apertures or to change format to individual one dimensional images. The task **scombine** is used to combine or merge orders into a single spectrum.

4. Package Parameters

The **echelle** package parameters, shown in Figure 1, set parameters which change infrequently and define the standard I/O functions.

Figure 1: Package Parameter Set for the ECHELLE Package

```
cl> epar echelle
                          I R A F
           Image Reduction and Analysis Facility
PACKAGE = imred
   TASK = echelle

(extinct= onedstds$kpnoextinct.dat) Extinction file
(caldir = onedstds$spechayescal/) Standard star calibration directory
(observa=  observatory) Observatory of data
(interp =        poly5) Interpolation type
(dispaxi=            2) Image axis for 2D images
(nsum   =            1) Number of lines/columns to sum for 2D images

(databas=     database) Database
(verbose=           no) Verbose output?
(logfile=      logfile) Text log file
(plotfil=             ) Plot file

(records=                     ) Record number extensions
(version= ECHELLE V3: July 1991)
```

The extinction file is used for making extinction corrections and the standard star calibration directory is used for determining flux calibrations from standard star observations. The calibration directories contain data files with standard star fluxes and band passes. The available extinction files and flux calibration directories may be listed using the command:

```
cl> page onedstds$README
```

The extinction correction requires computation of an air mass using the task **setairmass**. The air mass computation needs information about the observation and, in particular, the latitude of the observatory. This is determined using the OBSERVAT image header keyword. If this keyword is not present the observatory parameter is used. See the task **observatory** for more on defining the observatory parameters.

The spectrum interpolation type is used whenever a spectrum needs to be resampled for linearization or performing operations between spectra with different sampling. The "sinc" interpolation may be of interest as an alternative but see the cautions given in **onedspec.package**.

The verbose parameter selects whether to print everything which goes into the log file on the terminal. It is useful for monitoring everything that the task does. The log and plot files are useful for keeping a record of the processing. A log file is highly recommended. A plot file provides a record of the apertures, traces, and extracted spectra but can become quite large.

5. Processing Parameters

The **doecslit** parameters are shown in Figure 2.

Figure 2: Parameter Set for DOECSLIT

```
                          I R A F
            Image Reduction and Analysis Facility
PACKAGE = echelle
   TASK = doecslit

objects =               List of object spectra
(apref  =             ) Aperture reference spectrum
(arcs   =             ) List of arc spectra
(arctabl=             ) Arc assignment table (optional)
(standar=             ) List of standard star spectra

(readnoi=           0.) Read out noise sigma (photons)
(gain   =           1.) Photon gain (photons/data number)
(datamax=        INDEF) Max data value / cosmic ray threshold
(norders=           10) Number of orders
(width  =           5.) Width of profiles (pixels)

(dispcor=          yes) Dispersion correct spectra?
(extcor =           no) Extinction correct spectra?
(fluxcal=           no) Flux calibrate spectra?
(resize =           no) Resize object apertures?
(clean  =           no) Detect and replace bad pixels?
(trace  =          yes) Trace object spectra?
(backgro=         none) Background to subtract
(splot  =           no) Plot the final spectra?
(redo   =           no) Redo operations if previously done?
(update =           no) Update spectra if cal data changes?
(quicklo=           no) Approximate quicklook reductions?
(batch  =           no) Extract objects in batch?
(listonl=           no) List steps but don't process?

(sparams=             ) Algorithm parameters
```

The input images are specified by image lists. The lists may be a list of explicit comma separate image names, @ files, or image templates using pattern matching against file names in the directory. To allow wildcard image lists to be used safely and conveniently the image lists are checked to remove extracted images (the .ec images) and to automatically identify object and arc spectra. Object and arc images are identified by the keyword IMAGETYP with values of "object", "OBJECT", "comp", or "COMPARISON" (the current practice at NOAO). If arc images are found in the object list they are transferred to the arc list while if object images are found in the arc list they are ignored. All other image types, such as biases, darks, or flat fields, are ignored. This behavior allows simply specifying all images with a wildcard in the object list with automatic selections of arc spectra or a wildcard in the arc list to automatically find the arc spectra. If the data lack the identifying information it is up to the user to explicitly set the proper lists.

As mentioned earlier, all the arc images must be of the same type; that is taken with the same arc lamp. The aperture reference parameter is a single image name which is usually a bright star.

The next set of parameters describe the noise characteristics and the general layout of the orders. The read out noise and gain are used when "cleaning" cosmic rays and when using variance or optimal weighting. These parameters must be fairly accurate. Note that these are the effective parameters and must be adjusted if previous processing has

modified the pixel values; such as with an unnormalized flat field.

The general direction in which the orders run is specified by the dispersion axis parameter. Recall that ideally it is the direction of constant wavelength which should be aligned with an image axis and the dispersion direction will not be aligned because of the cross-dispersion. The `norders` parameter is used to automatically find the orders. The specified number of the brightest peaks are found. Generally after finding the orders the aperture definitions are reviewed and adjusted interactively. The profile width should be approximately the full width at the profile base. The default aperture limits and background regions are all derived from this width parameter.

The next set of parameters select the processing steps and options. The various calibration steps may be done simultaneously, that is at the same time as the basic extractions, or in separate executions of the task. Typically, all the desired operations are done at the same time. Dispersion correction requires at least one arc spectrum and flux calibration requires dispersion correction and at least one standard star observation.

The `resize` option resets the edges of the extraction apertures based on the profile for each object and standard star order. The default resizing is to the 5% point relative to the peak measured above the background. This allows following changes in the seeing. However, one should consider the consequences of this if attempting to flux calibrate the observations. Except in quicklook mode, the apertures for each object and standard star observation may be reviewed graphically and further adjustments made to the aperture width and background regions.

The apertures for each observation are adjusted for small shifts relative to the reference aperture definitions. If you think this is not sufficient, say to account for rotation of the detector or for differing atmospheric dispersion, the `trace` option allows redefining the aperture trace functions for each observation. Note this is only allowed in non-quicklook mode.

The `clean` option invokes a profile fitting and deviant point rejection algorithm as well as a variance weighting of points in the aperture. See the next section for more about requirements to use this option.

The `background` option selects a type of correction for background or scattered light. If the type is "scattered" a global scattered light is fit to the data between the apertures and subtracted from the images. *Note that the input images are modified by this operation*. This option is slow and is not allowed in quicklook mode. Alternatively, a local background may be subtracted using background regions defined for each aperture. The background may be within the slit for a sky subtraction or outside of the slit for a local scattered light subtraction. The data in the regions may be averaged, medianed, or the minimum value used. Another choice is to fit the data in the background regions by a function and interpolate to the object aperture.

Generally once a spectrum has been processed it will not be reprocessed if specified as an input spectrum. However, changes to the underlying calibration data can cause such spectra to be reprocessed if the `update` flag is set. The changes which will cause an update are a new reference image, adding the scattered light subtraction option, a new arc reference image, and new standard stars. If all input spectra are to be processed regardless of previous processing the `redo` flag may be used. Note that reprocessing clobbers the previously processed output spectra.

The final step is to plot the spectra if the `splot` option is selected. In non-quicklook mode there is a query which may be answered either in lower or upper case. The plotting uses the interactive task **splot**. In quicklook mode the plot appears noninteractively using the task **specplot**.

The `quicklook` option provides a simpler, less interactive, mode. The quicklook mode automatically assigns the reference apertures to the object and standard star observations without interactive review or tracing, does not do the time consuming scattered light correction, and the `splot` option selects a noninteractive plot to be shown at the end of processing of each object and standard star spectrum. While the algorithms used in quicklook mode are nearly the same as in non-quicklook mode and the final results may be the same it is recommended that the greater degree of monitoring and review in non-quicklook mode be used for careful final reductions.

The batch processing option allows object spectra to be processed as a background or batch job. This will occur only if the interactive `splot` option is not active; either not set, turned off during processing with "NO", or in quicklook mode. In batch processing the terminal output is suppressed.

The `listonly` option prints a summary of the processing steps which will be performed on the input spectra without actually doing anything. This is useful for verifying which spectra will be affected if the input list contains previously processed spectra. The listing does not include any arc spectra which may be extracted to dispersion calibrate an object spectrum.

The last parameter (excluding the task mode parameter) points to another parameter set for the algorithm parameters. The default parameter set is called **sparams**. The algorithm parameters are discussed further in the next section.

6. Algorithms and Algorithm Parameters

This section summarizes the various algorithms used by the **doecslit** task and the parameters which control and modify the algorithms. The algorithm parameters available to you are collected in the parameter set **sparams**. These parameters are taken from the various general purpose tasks used by the **doecslit** processing task. Additional information about these parameters and algorithms may be found in the help for the actual task executed. These tasks are identified below. The aim of this parameter set organization is to collect all the algorithm parameters in one place separate from the processing parameters and include only those which are relevant for echelle slit data. The parameter values can be changed from the defaults by using the parameter editor,

```
cl> epar sparams
```

or simple typing `sparams`. The parameter editor can also be entered when editing the **doecslit** parameters by typing `:e` when positioned at the `sparams` parameter. Figure 3 shows the parameter set.

Figure 3: Algorithm Parameter Set

```
cl> epar sparams
                          I R A F
           Image Reduction and Analysis Facility
PACKAGE = echelle
   TASK = sparams

(line   =        INDEF) Default dispersion line
(nsum   =           10) Number of dispersion lines to sum
(extras =           no) Extract sky, sigma, etc.?

                        -- AUTOMATIC APERTURE RESIZING PARAMETERS --
(ylevel =         0.05) Fraction of peak or intensity for resizing

                        -- TRACE PARAMETERS --
(t_step =           10) Tracing step
(t_funct=      spline3) Trace fitting function
(t_order=            2) Trace fitting function order
(t_niter=            1) Trace rejection iterations
(t_low  =           3.) Trace lower rejection sigma
(t_high =           3.) Trace upper rejection sigma

                        -- BACKGROUND AND SCATTERED LIGHT PARAMETERS --
(b_funct=     legendre) Background function
(b_order=            1) Background function order
(b_naver=         -100) Background average or median
(b_niter=            0) Background rejection iterations
(b_low  =           3.) Background lower rejection sigma
(b_high =           3.) Background upper rejection sigma
(buffer =           1.) Buffer distance from apertures
(apscat1=             ) Fitting parameters across the dispersion
(apscat2=             ) Fitting parameters along the dispersion

                        -- APERTURE EXTRACTION PARAMETERS --
(weights=         none) Extraction weights (none|variance)
(pfit   =        fit1d) Profile fitting algorithm (fit1d|fit2d)
(lsigma =           3.) Lower rejection threshold
(usigma =           3.) Upper rejection threshold

                                -- ARC DISPERSION FUNCTION PARAMETERS --
(coordli= linelist$thar.dat) Line list
(match  =           1.) Line list matching limit in Angstroms
(fwidth =           4.) Arc line widths in pixels
(cradius=          10.) Centering radius in pixels
```

```
(i_funct=     legendre) Echelle coordinate function
(i_xorde=            3) Order of coordinate function along dispersion
(i_yorde=            3) Order of coordinate function across dispersion
(i_niter=            3) Rejection iterations
(i_low  =           3.) Lower rejection sigma
(i_high =           3.) Upper rejection sigma
(refit  =          yes) Refit coordinate function when reidentifying

                        -- AUTOMATIC ARC ASSIGNMENT PARAMETERS --
(select =       interp) Selection method for reference spectra
(sort   =           jd) Sort key
(group  =          ljd) Group key
(time   =           no) Is sort key a time?
(timewra=          17.) Time wrap point for time sorting

                        -- DISPERSION CORRECTION PARAMETERS --
(lineari=          yes) Linearize (interpolate) spectra?
(log    =           no) Logarithmic wavelength scale?
(flux   =          yes) Conserve flux?

                        -- SENSITIVITY CALIBRATION PARAMETERS --
(bandwid=          10.) Bandpass widths
(bandsep=          10.) Bandpass separation
(s_inter=          yes) Graphic interaction to examine/define bandpasses
(s_funct=      spline3) Fitting function
(s_order=            1) Order of sensitivity function
(fnu    =           no) Create spectra having units of FNU?
```

6.1. Aperture Definitions

The first operation is to define the extraction apertures, which include the aperture width, background regions, and position dependence with wavelength, for the input echelle slit spectra and, if flux calibration is selected, the standard star spectra. This is done only for spectra which do not have previously defined apertures unless the `redo` option is set to force all definitions to be redone. Thus, apertures may be defined separately using the **apextract** tasks. This is particularly useful if one needs to use reference images to define apertures for very weak spectra which are not well centered or traced by themselves.

Initially apertures are defined for a specified *aperture reference* image. The selected number of orders are found automatically by selecting the highest peaks in a cut across the dispersion. Apertures are assigned with a width given by the `width` parameter and numbered sequentially. The background regions are also defined in terms of the width parameter starting at one width distance from the profile center and extending to two widths on both sides of the profile. As an example, if the width parameter is 5 pixels the default aperture limits are +/- 2.5 pixels and the background sample regions will be "-10:-5,5:10". If the `resize` parameter is set the aperture limits are adjusted to a specified point on the spectrum profile (see **apresize**).

A query is then given allowing the aperture definitions to be reviewed and modified. Queries made by **doecslit** generally may be answered with either lower case "yes" or "no" or with upper case "YES" or "NO". The upper case responses apply to all further queries and so are used to eliminate further queries of that kind.

Reviewing the aperture definitions is highly recommended to check the aperture numbering, aperture limits, and background regions. The aperture numbers must be linearly related, with a slope of +/- 1, to the true order numbers though absolute order numbers need not be known. The key point is that if an order is skipped the aperture numbers must also skip. The background regions are checked with the ’b’ key. Typically one adjusts all the background regions at the same time by selecting all apertures with the ’a’ key first. To exit the background and aperture editing steps type

Next the positions of the orders at various points along the dispersion are measured and "trace functions" are fit. The user is asked whether to fit each trace function interactively. This is selected to adjust the fitting parameters such as function type and order. When interactively fitting a query is given for each aperture. After the first aperture one may skip reviewing the other traces.

After the aperture reference image is done all the object and standard star images are checked for aperture definitions and those without definitions are assigned apertures. The assignment consists of inheriting the aperture from the reference aperture image, recentering the apertures based on an average shift that best centers all the apertures, resizing the apertures if the resize option is selected, and retracing the spectral orders if the retracing option is selected. Retracing is only allowed in non-quicklook mode (set by the `quicklook` parameter). Also interactive review of the aperture definitions is only done in non-quicklook mode. In quicklook mode the aperture definitions are all set noninteractively without retracing. It is recommended that quicklook only be used for initial quick extractions and calibration and that for final reductions one at least review the aperture definitions and possibly retrace each observation.

The above steps are all performed using tasks from the **apextract** package and parameters from the **sparams** parameters. As a quick summary, the dispersion direction of the spectra are determined from the package **dispaxis** parameter if not defined in the image header. The default line or column for finding the object position on the slit and the number of image lines or columns to sum are set by the `line` and `nsum` parameters. A line of INDEF (the default) selects the middle of the image. The automatic finding algorithm is described for the task **apfind** and basically finds the strongest peaks. The resizing is described in the task **apresize** and the parameters used are also described there. The tracing is done as described in **aptrace** and consists of stepping along the image using the specified `t_step` parameter. The function fitting uses the **icfit** commands with the other parameters from the tracing section.

6.2. Background or Scattered Light Subtraction

In addition to not subtracting any sky or scattered light there are two approaches to subtracting background light. The first is to determine a smooth global scattered light component. The second is to subtract a locally determined background at each point along the dispersion and for each aperture. This can be either for a sky subtraction if the background regions are within the slit or scattered light if the background regions are outside of the slit. Note that background subtraction is only done for object and standard star images and not for arc spectra. Also, the global scattered light option is not done in quicklook mode.

The global scattered light fitting and subtraction is done with the task **apscatter**. The function fitting parameters are set interactively using the aperture reference spectrum. All other subtractions are done noninteractively with the same set of parameters. The scattered light is subtracted from the input images, thus modifying them, and one might wish to first make backups of the original images.

The scattered light is measured between the apertures using a specified buffer distance from the aperture edges. The scattered light pixels are fit by a series of one dimensional functions across the dispersion. The independent fits are then smoothed along the dispersion by again fitting low order functions. These fits then define the smooth scattered light surface to be subtracted from the image. The fitting parameters are defined and recorded in the two parameter sets `apscat1` and `apscat2`. The scattered light algorithm is described more fully in **apscatter**. This algorithm is relatively slow.

Local background subtraction is done during extraction based on background regions and parameters defined by the default background parameters or changed during interactive review of the apertures. The background subtraction options are to subtract the average, median, or minimum of the pixels in the background regions, or to fit a function and subtract the function from under the extracted object pixels. The background regions are specified in pixels from the aperture center and follow changes in center of the spectrum along the dispersion. The syntax is colon separated ranges with multiple ranges separated by a comma or space. The background fitting uses the **icfit** routines which include medians, iterative rejection of deviant points, and a choice of function types and orders. Note that it is important to use a method which rejects cosmic rays such as using either medians over all the background regions (`background` = "median") or median samples during fitting (`b_naverage` < -1). The background subtraction algorithm and options are described in greater detail in **apsum** and **apbackground**.

6.3. Extraction

The actual extraction of the spectra is done by summing across the fixed width apertures at each point along the dispersion. The default is to simply sum the pixels using partial pixels at the ends. There is an option to weight the sum based on a Poisson variance model using the `readnoise` and `gain` detector parameters. Note that if the `clean` option is selected the variance weighted extraction is used regardless of the `weights` parameter. The sigma thresholds for cleaning are also set in the **sparams** parameters.

The cleaning and variance weighting options require knowing the effective (i.e. accounting for any image combining) read out noise and gain. These numbers need to be adjusted if the image has been processed such that the intensity scale has a different origin (such as a scattered light subtraction) or scaling (such as caused by unnormalized flat fielding). These options also require using background subtraction if the profile does not go to zero. For optimal

extraction and cleaning to work it is recommended that any flat fielding be done using flat fields produced by **apflatten**, no scattered light correction, and using background subtraction if there is any appreciable sky or to compensate for scattered light. For further discussion of cleaning and variance weighted extraction see **apvariance** and **approfiles** as well as **apsum**.

6.4. Dispersion Correction

If dispersion correction is not selected, `dispcor`=no, then the object spectra are simply extracted. The extracted spectra may be plotted by setting the `splot` option. This produces a query and uses the interactive **splot** task in non-quicklook mode and uses **specplot** noninteractively in quicklook mode.

Dispersion corrections are applied to the extracted spectra if the `dispcor` processing parameter is set. There are three basic steps involved; determining the dispersion functions relating pixel position to wavelength, assigning the appropriate dispersion function to a particular observation, and either storing the nonlinear dispersion function in the image headers or resampling the spectra to evenly spaced pixels in wavelength.

The first arc spectrum in the arc list is used to define the reference dispersion solution. It is extracted using the reference aperture definition. Note extractions of arc spectra are not background or scattered light subtracted. The interactive task **ecidentify** is used to define the dispersion function. The idea is to mark some lines in a few orders whose wavelengths are known (with the line list used to supply additional lines after the first few identifications define the approximate wavelengths) and to fit a function giving the wavelength from the aperture number and pixel position.

The arc dispersion function parameters are for **ecidentify** and it's related partner **ecreidentify**. The parameters define a line list for use in automatically assigning wavelengths to arc lines, a centering width (which should match the line widths at the base of the lines), the dispersion function type and orders, parameters to exclude bad lines from function fits, and defining whether to refit the dispersion function as opposed to simply determining a zero point shift. The defaults should generally be adequate and the dispersion function fitting parameters may be altered interactively. One should consult the help for the two tasks for additional details of these parameters and the interactive operation of **ecidentify**.

Once the reference dispersion function is defined other arc spectra are extracted as required by the object spectra. The assignment of arcs is done either explicitly with an arc assignment table (parameter `arctable`) or based on a header parameter such as a time. This assignments are made by the task **refspectra**. When two arcs are assigned to an object spectrum an interpolation is done between the two dispersion functions. This makes an approximate correction for steady drifts in the dispersion.

The tasks **setjd** and **setairmass** are automatically run on all spectra. This computes and adds the header parameters for the Julian date (JD), the local Julian day number (LJD), the universal time (UTMIDDLE), and the air mass at the middle of the exposure. The default arc assignment is to use the Julian date grouped by the local Julian day number. The grouping allows multiple nights of data to be correctly assigned at the same time.

In non-quicklook mode the arc spectra assigned to each object are extracted using the same apertures as the object. This accounts for changes in the recentering, aperture sizes, and tracing functions. In quicklook mode the arc spectra are extracted using the reference apertures. When the same arc is used for several object images this allows the arc spectrum to only be extracted once.

Defining the dispersion function for a new arc extraction is done with the task **ecreidentify**. This is done noninteractively with log information recorded about the line reidentifications and the fit.

The last step of dispersion correction is setting the dispersion of the object image from the arc images. There are two choices here. If the `linearize` parameter is not set the nonlinear dispersion function is stored in the image header. Other IRAF tasks interpret this information when dispersion coordinates are needed for plotting or analysis. This has the advantage of not requiring the spectra to be interpolated and the disadvantage that the dispersion information is only understood by IRAF tasks and cannot be readily exported to other analysis software.

If the `linearize` parameter is set then the spectra are resampled to a linear dispersion relation either in wavelength or the log of the wavelength. For echelle spectra each order is linearized independently so that the wavelength interval per pixel is different in different orders. This preserves most of the resolution and avoids over or under sampling of the highest or lowest dispersion orders. The wavelength limits are taken from the limits determined from the arc reference spectrum and the number of pixels is the same as the original images. The dispersion per pixel is then derived from these constraints.

The linearization algorithm parameters allow selecting the interpolation function type, whether to conserve flux per pixel by integrating across the extent of the final pixel, and whether to linearize to equal linear or logarithmic intervals. The latter may be appropriate for radial velocity studies. The default is to use a fifth order polynomial for interpolation, to conserve flux, and to not use logarithmic wavelength bins. These parameters are described fully in

the help for the task **dispcor** which performs the correction.

6.5. Flux Calibration

Flux calibration consists of an extinction correction and an instrumental sensitivity calibration. The extinction correction only depends on the extinction function defined by the package parameter `extinct` and determination of the airmass from the header parameters (the air mass is computed by **setairmass** as mentioned earlier). The sensitivity calibration depends on a sensitivity calibration spectrum determined from standard star observations for which there are tabulated absolute fluxes. The task that applies both the extinction correction and sensitivity calibration to each extracted object spectrum is **calibrate**. Consult the manual page for this task for more information.

Generation of the sensitivity calibration spectrum is done before processing any object spectra since it has two interactive steps and requires all the standard star observations. The first step is tabulating the observed fluxes over the same bandpasses as the calibrated absolute fluxes. For very high resolution it may be the case that the measured calibration bandpasses are too large or sparse. In this case one must interpolate the calibration data to bandpasses appropriate for the data. If the bandpass widths and separations are given as INDEF then the same bandpasses as in the calibration file are used. Otherwise a uniform grid of bandpasses is interpolated. Using interpolated bandpasses is not rigorous but is sometimes the only choice for echelle spectra.

The standard star tabulations are done after each standard star is extracted and dispersion corrected. You are asked for the name of the standard star as tabulated in the absolute flux data files in the directory `caldir` defined by the package parameters. If the `interact` parameter is yes the bandpasses can be displayed on the data and you can interactively add or delete bandpasses. The tabulation of the standard star observations over the standard bandpasses is done by the task **standard**. The tabulated data is stored in the file `std`. Note that if the `redo` flag is not set any new standard stars specified in subsequent executions of **doecslit** are added to the previous data in the data file, otherwise the file is first deleted. Modification of the tabulated standard star data, such as by adding new stars, will cause any spectra in the input list which have been previously calibrated to be reprocessed if the `update` flag is set.

After the standard star calibration bandpass fluxes are tabulated the information from all the standard stars is combined to produce a sensitivity function for use by **calibrate**. The sensitivity function determination is interactive and uses the task **sensfunc**. This task allows fitting a smooth sensitivity function to the ratio of the observed to calibrated fluxes verses wavelength. The types of manipulations one needs to do include deleting bad observations, possibly removing variable extinction (for poor data), and possibly deriving a revised extinction function. This is a complex operation and one should consult the manual page for **sensfunc**. The sensitivity function is saved as one dimensional spectra (one per order) with the root name `sens`. Deletion of these images will also cause reprocessing to occur if the `update` flag is set.

7. References

7.1. IRAF Introductory References

Work is underway on a new introductory guide to IRAF. Currently, the work below is the primary introduction.

P. Shames and D. Tody, *A User's Introduction to the IRAF Command Language*, Central Computer Services, NOAO, 1986.

7.2. CCD Reductions

F. Valdes, *The IRAF CCD Reduction Package -- CCDRED*, Central Computer Services, NOAO, 1987.

F. Valdes, *User's Guide to the CCDRED Package*, Central Computer Services, NOAO, 1988. Also on-line as `help ccdred.guide`.

P. Massey, *A User's Guide to CCD Reductions with IRAF*, Central Computer Services, NOAO, 1989.

7.3. Aperture Extraction Package

F. Valdes, *The IRAF APEXTRACT Package*, Central Computer Services, NOAO, 1987 (out-of-date).

7.4. Task Help References

Each task in the **specred** packages and tasks used by **dofibers** have help pages describing the parameters and task in some detail. To get on-line help type

`cl> help` *taskname*

The output of this command can be piped to **lprint** to make a printed copy.

```
      apall - Extract 1D spectra (all parameters in one task)
  apdefault - Set the default aperture parameters and apidtable
     apedit - Edit apertures interactively
     apfind - Automatically find spectra and define apertures
      apfit - Fit 2D spectra and output the fit, difference, or ratio
  apflatten - Remove overall spectral and profile shapes from flat fields
     apmask - Create and IRAF pixel list mask of the apertures
apnormalize - Normalize 2D apertures by 1D functions
 aprecenter - Recenter apertures
   apresize - Resize apertures
  apscatter - Fit and subtract scattered light
      apsum - Extract 1D spectra
    aptrace - Trace positions of spectra

      bplot - Batch plots of spectra
  calibrate - Apply extinction and flux calibrations to spectra
  continuum - Fit the continuum in spectra
   deredden - Apply interstellar extinction corrections
    dispcor - Dispersion correct spectra
     dopcor - Doppler correct spectra
 ecidentify - Identify features in spectrum for dispersion solution
ecreidentify - Automatically identify features in spectra
 refspectra - Assign wavelength reference spectra to other spectra
     sarith - Spectrum arithmetic
   scombine - Combine spectra
      scopy - Select and copy apertures in different spectral formats
   sensfunc - Create sensitivity function
 setairmass - Compute effective airmass and middle UT for an exposure
      setjd - Compute and set Julian dates in images
      slist - List spectrum header parameters
   specplot - Stack and plot multiple spectra
      splot - Preliminary spectral plot/analysis
   standard - Identify standard stars to be used in sensitivity calc

   doecslit - Process Echelle slit spectra
      demos - Demonstrations and tests

            Additional help topics

   onedspec.package - Package parameters and general description of package
  apextract.package - Package parameters and general description of package
 approfiles - Profile determination algorithms
 apvariance - Extractions, variance weighting, cleaning, and noise model
   center1d - One dimensional centering algorithm
      icfit - Interactive one dimensional curve fitting
```

Appendix A: DOECSLIT Parameters

objects

List of object images to be processed. Previously processed spectra are ignored unless the `redo` flag is set or the `update` flag is set and dependent calibration data has changed. If the images contain the keyword IMAGETYP then only those with a value of "object" or "OBJECT" are used and those with a value of "comp" or "COMPARISON" are added to the list of arcs. Extracted spectra are ignored.

apref = ""

Aperture reference spectrum. This spectrum is used to define the basic extraction apertures and is typically a bright star spectrum.

arcs = "" (at least one if dispersion correcting)

List of arc calibration spectra. These spectra are used to define the dispersion functions. The first spectrum is

used to mark lines and set the dispersion function interactively and dispersion functions for all other arc spectra are derived from it. If the images contain the keyword IMAGETYP then only those with a value of "comp" or "COMPARISON" are used. All others are ignored as are extracted spectra.

arctable = "" (optional) (refspectra)
Table defining which arc spectra are to be assigned to which object spectra (see **refspectra**). If not specified an assignment based on a header parameter, `sparams.sort`, such as the Julian date is made.

standards = "" (at least one if flux calibrating)
List of standard star spectra. The standard stars must have entries in the calibration database (package parameter `echelle.caldir`).

readnoise = 0., gain = 1. (apsum)
Read out noise in photons and detector gain in photons per data value. This parameter defines the minimum noise sigma and the conversion between photon Poisson statistics and the data number statistics. Image header keywords (case insensitive) may be specified to obtain the values from the image header.

datamax = INDEF (apsum.saturation)
The maximum data value which is not a cosmic ray. When cleaning cosmic rays and/or using variance weighted extraction very strong cosmic rays (pixel values much larger than the data) can cause these operations to behave poorly. If a value other than INDEF is specified then all data pixels in excess of this value will be excluded and the algorithms will yield improved results. This applies only to the object spectra and not the standard star or arc spectra. For more on this see the discussion of the saturation parameter in the **apextract** package.

norders = 10 (apfind)
Number of orders to be found automatically.

width = 5. (apedit)
Approximate full width of the spectrum profiles. This parameter is used to define a width and error radius for the profile centering algorithm, and defaults for the aperture limits and background regions.

dispcor = yes
Dispersion correct spectra? This may involve either defining a nonlinear dispersion coordinate system in the image header or resampling the spectra to uniform linear wavelength coordinates as selected by the parameter `sparams.linearize`.

extcor = no
Extinction correct the spectra?

fluxcal = no
Flux calibrate the spectra using standard star observations?

resize = no (apresize)
Resize the default apertures for each object based on the spectrum profile?

clean = no (apsum)
Detect and correct for bad pixels during extraction? This is the same as the clean option in the **apextract** package. If yes this also implies variance weighted extraction. In addition the datamax parameters can be useful.

trace = yes (non-quicklook mode only) (aptrace)
Allow tracing each object spectrum separately? If not set then the trace from the aperture reference is used, with recentering to allow for shifts across the dispersion. If set then each object and standard star image is retraced. Retracing is NOT done in quicklook mode.

background = "none" (apsum, apscatter)
Type of background light subtraction. The choices are "none" for no background subtraction, "scattered" for a global scattered light subtraction, "average" to average the background within background regions, "median" to use the median in background regions, "minimum" to use the minimum in background regions, or "fit" to fit across the dispersion using the background within background regions. The scattered light option fits and subtracts a smooth global background and modifies the input images. This is a slow operation and so is NOT performed in quicklook mode. The other background options are local to each aperture. The "fit" option uses additional fitting parameters from **sparams** and the "scattered" option uses parameters from **apscat1** and **apscat2**.

splot = no
Plot the final spectra? In quicklook mode a noninteractive, stacked plot is automatically produced using the task **specplot** while in non-quicklook mode a query is given and the task **splot** is used for interactive plotting.

redo = no
Redo operations previously done? If no then previously processed spectra in the objects list will not be processed unless required by the update option.

update = no
Update processing of previously processed spectra if the aperture reference image, the dispersion reference image, or standard star calibration data are changed?

quicklook = no
Extract and calibrate spectra with minimal interaction? In quicklook mode only aperture reference definitions, the initial dispersion function solution, and the standard star setup are done interactively. Scattered light subtraction and individual object tracing are not performed. Normally the `splot` option is set in this mode to produce an automatic final spectrum plot for each object. It is recommended that this mode not be used for final reductions.

batch = no
Process spectra as a background or batch job provided there are no interactive steps remaining.

listonly = no
List processing steps but don't process?

sparams = "" (pset)
Name of parameter set containing additional processing parameters. This parameter is only for indicating the link to the parameter set **sparams** and should not be given a value. The parameter set may be examined and modified in the usual ways (typically with "epar sparams" or ":e sparams" from the parameter editor). The parameters are described below.

-- GENERAL PARAMETERS --

line = INDEF, nsum = 10
The dispersion line (line or column perpendicular to the dispersion axis) and number of adjacent lines (half before and half after unless at the end of the image) used in finding, recentering, resizing, editing, and tracing operations. A line of INDEF selects the middle of the image along the dispersion axis.

extras = no (apsum)
Include raw unweighted and uncleaned spectra, the background spectra, and the estimated sigma spectra in a three dimensional output image format. See the discussion in the **apextract** package for further information.

-- AUTOMATIC APERTURE RESIZING PARAMETERS --

ylevel = 0.05 (apresize)
Fraction of the peak to set aperture limits during automatic resizing.

-- TRACE PARAMETERS --

t_step = 10 (aptrace)
Step along the dispersion axis between determination of the spectrum positions. Note the `nsum` parameter is also used to enhance the signal-to-noise at each step.

t_function = "spline3", t_order = 2 (aptrace)
Default trace fitting function and order. The fitting function types are "chebyshev" polynomial, "legendre" polynomial, "spline1" linear spline, and "spline3" cubic spline. The order refers to the number of terms in the polynomial functions or the number of spline pieces in the spline functions.

t_niterate = 1, t_low = 3., t_high = 3. (aptrace)
Default number of rejection iterations and rejection sigma thresholds.

-- BACKGROUND AND SCATTERED LIGHT PARAMETERS --

b_function = "legendre", b_order = 1 (apsum)
Default background fitting function and order. The fitting function types are "chebyshev" polynomial, "legendre" polynomial, "spline1" linear spline, and "spline3" cubic spline. The order refers to the number of terms in the polynomial functions or the number of spline pieces in the spline functions.

b_naverage = -100 (apsum)
Default number of points to average or median. Positive numbers average that number of sequential points to form a fitting point. Negative numbers median that number, in absolute value, of sequential points. A value of 1 does no averaging and each data point is used in the fit.

b_niterate = 0 (apsum)
Default number of rejection iterations. If greater than zero the fit is used to detect deviant fitting points and reject them before repeating the fit. The number of iterations of this process is given by this parameter.

b_low_reject = 3., b_high_reject = 3. (apsum)
Default background lower and upper rejection sigmas. If greater than zero points deviating from the fit below and above the fit by more than this number of times the sigma of the residuals are rejected before refitting.

buffer = 1. (apscatter)
Buffer distance from the edge of any aperture for data to be included in the scattered light determination. This parameter may be modified interactively.

apscat1 = "", apscat2 = "" (apscatter)
Parameter sets for the fitting functions across and along the dispersion. These parameters are those used by **icfit**. These parameters are usually set interactively.

-- APERTURE EXTRACTION PARAMETERS --

weights = "none" (apsum) (none|variance)
Type of extraction weighting. Note that if the `clean` parameter is set then the weights used are "variance" regardless of the weights specified by this parameter. The choices are:

"none"
The pixels are summed without weights except for partial pixels at the ends.

"variance"
The extraction is weighted by the variance based on the data values and a poisson/ccd model using the `gain` and `readnoise` parameters.

pfit = "fit1d" (apsum and approfile) (fit1d|fit2d)
Type of profile fitting algorithm to use. The "fit1d" algorithm is preferred except in cases of extreme tilt.

lsigma = 3., usigma = 3. (apsum)
Lower and upper rejection thresholds, given as a number of times the estimated sigma of a pixel, for cleaning.

-- ARC DISPERSION FUNCTION PARAMETERS --

threshold = 10. (identify/reidentify)
In order for a feature center to be determined the range of pixel intensities around the feature must exceed this threshold.

coordlist = "linelist$thar.dat" (ecidentify)
Arc line list consisting of an ordered list of wavelengths. Some standard line lists are available in the directory "linelist$".

match = 1. (ecidentify)
The maximum difference for a match between the dispersion function computed value and a wavelength in the coordinate list.

fwidth = 4. (ecidentify)
Approximate full base width (in pixels) of arc lines.

cradius = 10. (reidentify)
Radius from previous position to reidentify arc line.

i_function = "legendre", i_xorder = 3, i_yorder = 3 (ecidentify)
The default function, function order for the pixel position dependence, and function order for the aperture number dependence to be fit to the arc wavelengths. The functions choices are "chebyshev" or "legendre".

i_niterate = 3, i_low = 3.0, i_high = 3.0 (ecidentify)
Number of rejection iterations and sigma thresholds for rejecting arc lines from the dispersion function fits.

refit = yes (ecreidentify)
Refit the dispersion function? If yes and there is more than 1 line and a dispersion function was defined in the arc reference then a new dispersion function of the same type as in the reference image is fit using the new pixel positions. Otherwise only a zero point shift is determined for the revised fitted coordinates without changing the form of the dispersion function.

-- AUTOMATIC ARC ASSIGNMENT PARAMETERS --

select = "interp" (refspectra)
Selection method for assigning wavelength calibration spectra. Note that an arc assignment table may be used to override the selection method and explicitly assign arc spectra to object spectra. The automatic selection methods are:

average
Average two reference spectra without regard to any sort parameter. If only one reference spectrum is specified then it is assigned with a warning. If more than two reference spectra are specified then only the first two are used and a warning is given. This option is used to assign two reference spectra, with equal weights, independent of any sorting parameter.

following
Select the nearest following spectrum in the reference list based on the sorting parameter. If there is no following spectrum use the nearest preceding spectrum.

interp
Interpolate between the preceding and following spectra in the reference list based on the sorting parameter. If there is no preceding and following spectrum use the nearest spectrum. The interpolation is weighted by the relative distances of the sorting parameter.

match
Match each input spectrum with the reference spectrum list in order. This overrides the reference aperture check.

nearest
Select the nearest spectrum in the reference list based on the sorting parameter.

preceding
Select the nearest preceding spectrum in the reference list based on the sorting parameter. If there is no preceding spectrum use the nearest following spectrum.

sort = "jd" (setjd and refspectra)
Image header keyword to be used as the sorting parameter for selection based on order. The header parameter must be numeric but otherwise may be anything. Common sorting parameters are times or positions.

group = "ljd" (setjd and refspectra)
Image header keyword to be used to group spectra. For those selection methods which use the group parameter the reference and object spectra must have identical values for this keyword. This can be anything but it must be constant within a group. Common grouping parameters are the date of observation "date-obs" (provided it does not change over a night) or the local Julian day number.

time = no, timewrap = 17. (refspectra)
Is the sorting parameter a 24 hour time? If so then the time origin for the sorting is specified by the timewrap parameter. This time should precede the first observation and follow the last observation in a 24 hour cycle.

-- DISPERSION CORRECTION PARAMETERS --

linearize = yes (dispcor)
Interpolate the spectra to a linear dispersion sampling? If yes the spectra will be interpolated to a linear or log linear sampling using the linear dispersion parameters specified by other parameters. If no the nonlinear dispersion function(s) from the dispersion function database are assigned to the input image world coordinate system and the spectral data is not interpolated. Note the interpolation function type is set by the package parameter `interp`.

log = no (ecdispcor)
Use linear logarithmic wavelength coordinates? Linear logarithmic wavelength coordinates have wavelength intervals which are constant in the logarithm of the wavelength.

flux = yes (ecdispcor)
Conserve the total flux during interpolation? If `no` the output spectrum is interpolated from the input spectrum at each output wavelength coordinate. If `yes` the input spectrum is integrated over the extent of each output pixel. This is slower than simple interpolation.

-- SENSITIVITY CALIBRATION PARAMETERS --

bandwidth = 10., bandsep = 10. (standard)
Interpolated bandpass grid. If INDEF then the same bandpasses as in the calibration files are used otherwise the calibration data is interpolated to the specified set of bandpasses.

s_interact = yes (standard)
Display the bandpasses on the standard star data and allow interactive addition and deletion of bandpasses.

s_function = "spline3", s_order = 1 (sensfunc)
Function and order used to fit the sensitivity data. The function types are "chebyshev" polynomial, "legendre" polynomial, "spline3" cubic spline, and "spline1" linear spline. Order of the sensitivity fitting function. The value corresponds to the number of polynomial terms or the number of spline pieces. The default values may be changed interactively.

fnu = no (calibrate)
The default calibration is into units of F-lambda. If `fnu` = yes then the calibrated spectrum will be in units of F-nu.

PACKAGE PARAMETERS

dispaxis = 2
Default dispersion axis. The dispersion axis is 1 for dispersion running along image lines and 2 for dispersion running along image columns. If the image header parameter DISPAXIS is defined it has precedence over this parameter. The default value defers to the package parameter of the same name.

extinction = "onedstds$kpnoextinct.dat" (standard, sensfunc, calibrate)
Extinction file for a site. There are two extinction files in the NOAO standards library, onedstds$, for KPNO and CTIO. These extinction files are used for extinction and flux calibration.

caldir (standard)
Standard star calibration directory. A directory containing standard star data files. Note that the directory name must end with '/'. There are a number of standard star calibrations directories in the NOAO standards library, onedstds$.

observatory = "observatory" (observatory)
The default observatory to use for latitude dependent computations. If the OBSERVAT keyword in the image header it takes precedence over this parameter.

interp = "poly5" (nearest|linear|poly3|poly5|spline3|sinc) (dispcor)
Spectrum interpolation type used when spectra are resampled. The choices are:

```
nearest - nearest neighbor
 linear - linear
  poly3 - 3rd order polynomial
```

```
  poly5 - 5th order polynomial
spline3 - cubic spline
   sinc - sinc function
```

database = "database"
Database name used by various tasks. This is a directory which is created if necessary.

verbose = no
Verbose output? If set then almost all the information written to the logfile is also written to the terminal except when the task is a background or batch process.

logfile = "logfile"
If specified detailed text log information is written to this file.

plotfile = ""
If specified metacode plots are recorded in this file for later review. Since plot information can become large this should be used only if really desired.

ENVIRONMENT PARAMETERS

The environment parameter *imtype* is used to determine the extension of the images to be processed and created. This allows use with any supported image extension. For STF images the extension has to be exact; for example "d1h".