



ANGLO-AUSTRALIAN OBSERVATORY

The 2dfdr Data Reduction System Users Manual

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1 Introduction

This document describes the data reduction software system known as 2dfdr. The name originates from “2dF data reduction” as it was originally dedicated to reducing data from the 2dF instrument. However, it now also reduces data from the 6dF, SPIRAL, and LDSS instruments, and is currently being upgraded to reduce data from the new AAOmega instrument.

The system is designed to provide interactive or partially automatic on-line reduction of data. A Graphical User Interface (GUI) is provided to interact with the user and thereby control the data reduction and allow inspection of reduced spectra.

The system currently does bias and dark subtraction, flat fielding, tram-line mapping to the fibre locations on the CCD, fibre extraction, arc identification, wavelength calibration, fibre throughput calibration and sky subtraction.

In general, reductions are extremely straightforward, and many users will only ever need to read section 2. However, the system is complex, and much of this manual is concerned with the many things that can go wrong.

The system was originally developed by Jeremy Bailey for the AAO.

2 Getting Started

2.1 Obtaining 2dfdr

The latest version of 2dfdr, built for various operating systems, can be found on the 2dF web pages on the AAO web site (<http://www.aao.gov.au/2df>)¹.

2.2 Required Data Files

To reduce a data set at least the following set of files should be available:

1. At least one fibre flat field exposure (class MFFFF). These exposures are made with a quartz lamp that provides a uniform spectrum. They are used to calibrate the detector, and to find centre and profile of the spectra.
2. At least one arc exposure (class MFARC). These exposures are made with lamps having various known strong lines. They are used to calibrate the central wavelength and dispersion.

¹ The document “2dfdr Maintenance Guide”, AAO Software Report 107, describes in detail how to obtain the required source files from the AAO version control system (acmm), and then use them to build the executables. This ensures the latest version is obtained. This will generally only be of use to AAO staff involved in the development of 2dfdr. Most people, in particular astronomers with 2dF data to reduce, will want to obtain the pre-built executables as described above.

3. One or more exposures on the target field (class MFOBJECT).

The system can also handle offset sky (class MFSKY), bias (class BIAS), dark (class DARK), and long slit (full chip) flat field (class LFLAT) exposures. Offset sky exposures are one of several methods used for sky calibration. It has generally not been found necessary to take bias and dark exposures as they contain little structure. There is no simple way with 2dF (or 6dF) to take a full chip flat, though one can be created by median filtering an MFFFF frame in the spectral direction, and AAOmega will allow routine LFLAT exposures. It is still possible to reduce the data if the full set of files listed above is not available, but some calibration stages may be skipped. Lack of an MFARC frame will result in garbage reductions.

Input files can be in either FITS (with extension .fits) or Starlink NDF (with extension .sdf) data format. The output files generated by 2dfdr can also be either FITS or NDF. All actual processing is carried out in the native NDF format with files automatically being converted to and from FITS at the beginning and end of the processing. Note that input data files should be either FITS or NDF and **not both**. If input data files of both formats are found with the same prefix, 2dfdr will give an error on loading the files.

2.3 Running the System

The data reduction system runs under Solaris and various versions of the Redhat Linux operating system. See the 2dF web page (<http://www.aao.gov.au/2df>) for details of the current operating system versions supported.

The X windows display device should be set appropriately for the workstation, by setting the DISPLAY environment variable or using a command such as the Starlink `xdisplay` command.

If you are using a monitor/display board with only 8 bits of colour information, it is often necessary to close down any X windows applications that use a lot of colour table entries before running the system. Otherwise, this may prevent the system from creating its display windows. Netscape is one application that can cause this problem. Trying running it as “`netscape -ncols 128`”.

To start the system first initialize the environment variables using the following shell commands:

```
setenv DRCONTROL_DIR {release-directory}
source $DRCONTROL_DIR/2dfdr_setup
```

where the `release-directory` is, for example, `/home/rwh/2dfdr-linux_x86`. Then go to the directory containing the data and start 2dfdr using the following command:

```
drcontrol &
```

This starts the system for the default 2dF instrument. On startup `drcontrol` looks for a `.idx` file in the `DRCONTROL_DIR` directory. This file configures the GUI for a particular instrument (e.g. 2dF, 6dF etc) and defines the default reduction parameters. The default `.idx` file is

2df.idx, however other set ups can be invoked by giving the name of the .idx file on the command line, e.g:

```
drcontrol 6df.idx &
```

which will start up 2dfdr for use with 6dF. Other .idx files include:

- 6df.idx - 6dF data reduction.
- rave.idx - 6dF RAVE (high dispersion stellar) data reduction.
- 2dfgrs.idx - 2dF data reduction with options used for the 2dF Galaxy Redshift Survey. This is suitable for a wide range of likely targets.
- 2dfns.idx - 2dF data reduction with options suitable for Nod & Shuffle data reduction.
- 2df_focus.idx - 2dF data reduction with defaults suitable for reduction of Hartmann pairs for spectrograph focus.
- spiral.idx - SPIRAL data reduction.
- ldss.idx - LDSS data reduction.

The 2dfdr_setup script also defines aliases that can be used to pick the most common .idx files: grsdrcontrol is the equivalent of running drcontrol with the 2dfgrs.idx file; drfocus is similarly used for the 2df_focus.idx file. User specified .idx files may be accessed by putting the full path on the command line, e.g.:

```
drcontrol /home/me/idx_files/my.idx &
```

will use the file my.idx in the directory /home/me/idx_files/.

On start up you will be prompted to select either NDF or FITS as the output data format. Alternatively you can make this decision on the command line using:

```
drcontrol 2df.idx ndf &
```

or

```
drcontrol 2df.idx fits &
```

Note that you must specify the .idx file to be used if you also wish to specify the output data format.

The Data reduction system is closed down by the **EXIT** command in the **File** menu.



Due to a problem in the Starlink libraries used by 2dfdr, the value for DRCONTROL_DIR must not exceed 40 characters. Getting this wrong will cause the plotting facilities to fail.

2.4 Start up Problems .

Type `cleanup` if there are problems starting the system or there are timeouts on the initialization. This command is available if the DRAMA system has been started. It shuts down the entire 2dfdr system, and should allow a clean restart once any problems have been resolved.

The most common problem on startup is 'can't allocate enough colour cells for display windows...'. Close all netscape sessions - including orphan ones revealed by `ps` - and any other colour-hungry applications.

It will also fail if there is no disc space available.

2.5 The User Interface

The user interface main window is shown in Figure 1. It is divided into three main sections. On the left is a panel that has a number of pages, which can be selected by means of tabs. One of these pages is the **Data** page (shown), which can be used to select data files by run number or file name, and then perform operations on them. The other tabbed pages in this section are used to set parameters which control the data reduction or display.

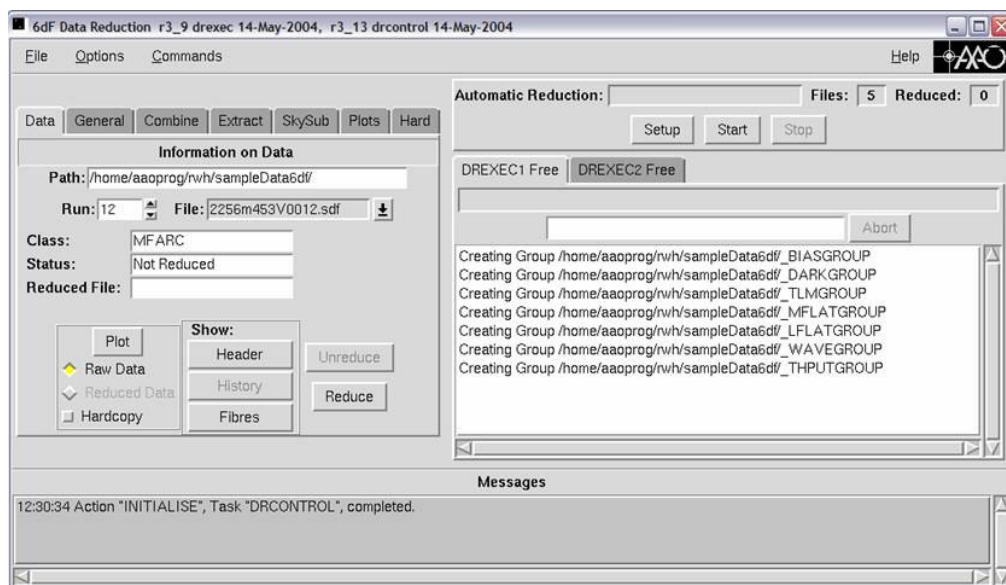


Figure 1: The 2dfdr main window

At the top right section of the screen is the **Automatic Reduction** panel, and below this is another tabbed panel that displays the progress of current operations and any messages output during the reduction progress. There are two execution tasks (DREXEC1 and DREXEC2), and each corresponds to a tab on the panel.

2.6 Reducing Data

The standard way of automatically reducing a data set is as follows:

1. Click on the **Setup** button in the **Automatic Reduction** section of the display. This will bring up a dialog, which should show the directory and root name of the data files. When these are correct click the **OK** button.
2. The system will now locate all the raw data files in the given directory and check their classes. It will also check if there are corresponding reduced and tramline map files. Once this is done, the **Data** tabbed page can be used to step through the files by run number or file name. This selects a file on which to work. Note that generally a new directory is made by the user for each new 2df field configuration (**although this is not absolutely necessary**).
3. If this is 2dF data and the first set for this spectrograph setup (for example following a grating change, or more generally whenever a new configuration is being observed) the **Find Fibres...** item in the **Commands** menu will probably be needed to create new fibre position files as described in Section 3.3.2. Note that there are four of these files, one for each slit assembly and spectrograph combination. Although not strictly required, it is generally easiest to run **Find Fibres...** for each new 2df field configuration. 6dF users do not need to run **Find Fibres**.
4. If parameters other than the defaults are desired, they should be set at this stage (e.g. a different extraction method, or sky subtraction method). The parameters are set in the tabbed pages in the left section labelled **Extract**, **SkySub**, etc.
5. Now click on the **Start** button in the **Automatic Reduction** section and the system will reduce all files in sequence. The system will automatically choose a sequence of reduction that ensures that calibration files are reduced before the runs they calibrate. Thus all flat fields are reduced first, then arcs, offset sky and finally object frames.

In principle this is all that is required to reduce data.

Data files can also be reduced individually. To do this, select the file in the **Data** tabbed page and click on the **Reduce** button. It is usually a good idea to reduce at least the first flat and arc individually, to check that all looks sensible (Section 2.8), before doing automatic reduction of the remaining frames.

Whether automatic or manual reduction is used, the file will be reduced in one of the two DREXEC tasks, and reduction status messages will be displayed in the appropriate window. The correct page of the tabbed widget must be selected for the DREXEC task being used to see the messages and progress bar.

2.7 Plotting Data

The **Plot** button in the **Data** tabbed page can be used to plot the currently selected run. Either the raw data or the reduced data can be plotted. The data will appear in the plot window with the title **DRPLOT2 - General Plots**.

Data for one run can be plotted while reduction of the next is in progress.

Selecting the hardcopy option will cause a file with the name gks74.ps, (or gks74.ps.2, gks74.ps.3, etc. for subsequent plots – a STARLINK file naming convention) to be generated. The “Hard” parameters page allows the user to select different kinds of hardcopy plots.

It is also possible to plot an individual data file using the **Plot** command from the **Commands** menu.

2.8 Did it Work?

Having reduced a set of data there are two important checks that users should make to ensure that the reduction has gone properly.

- Plot the tramline map and check that it overlays the data.
- Check that the arc reduction is satisfactory.

2.8.1 Tram map

To plot the tramline map, select the **Plot Tram Map...** item from the **Commands** menu. That will put up a file selection dialog showing files with names having a `tlm` suffix. There should be one of these generated from the first file to be reduced, normally a flat field. Select a file and a plot of the tramline map, overlaid on the flat field image it was derived from, will be plotted. To see what is happening, zoom the plot several times which is done by pressing the **Z** key on the keyboard with the cursor in the plot window. The plot can be panned to centre on the cursor position by pressing the **P** key, or zoom out using the **O** key. The tramlines should run down the centre of the data for each fibre as shown in Figure 2. See Section 3.3 if they don't. Of course, the tramline map is best checked during the data reduction. This can be done by selecting the **Plot Tram Map** option on the **Extract** page.

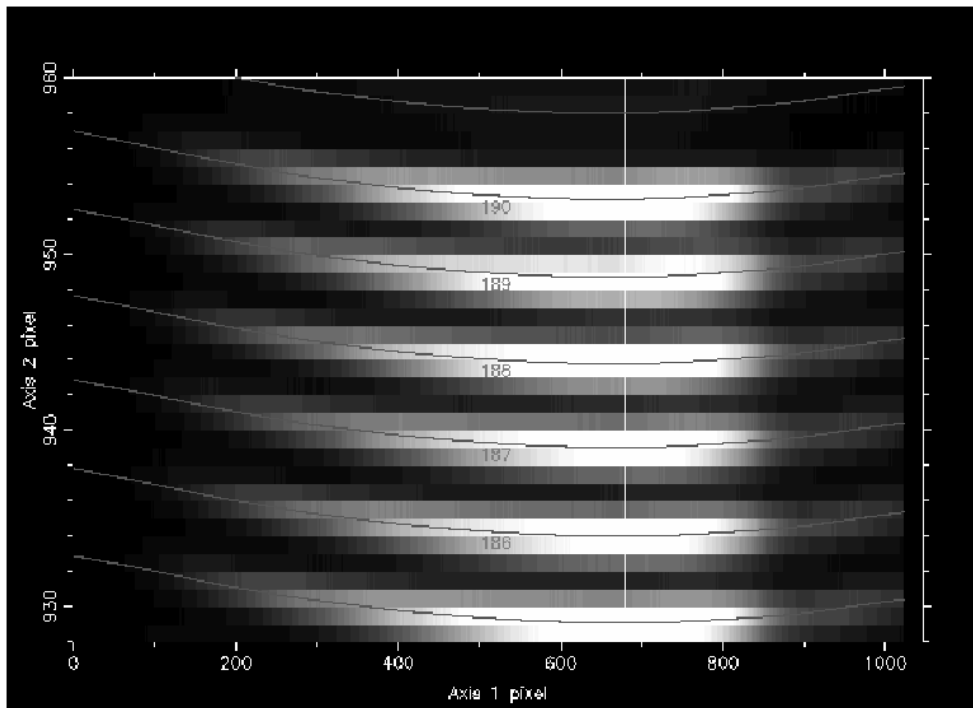


Figure 2: Typical result from the Plot Tram Map... option (after zooming the plot several times using the Z key). The tramlines run through the centre of the data on which they are overlaid.

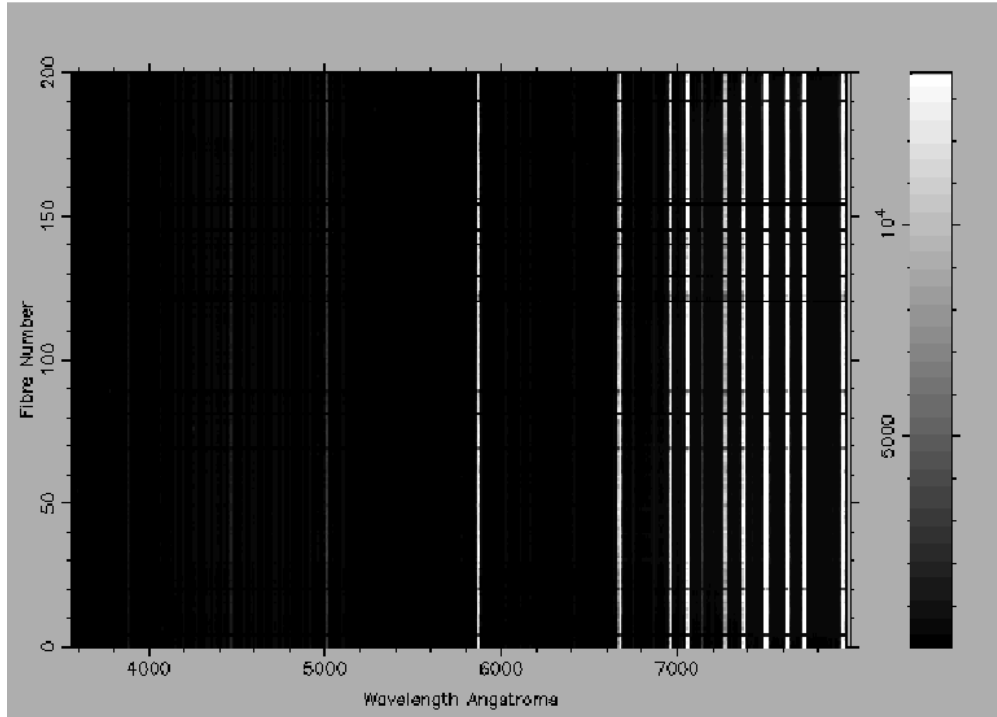


Figure 3: Correct appearance of a reduced arc exposure. The lines run straight up the image as all fibres have been rebinned to the same wavelength scale. Compare with Figure 4.

2.8.2 Arc file reduction

To check the arc reduction select the arc file in the **Data** tabbed page and plot the reduced file using the **Plot** button. The plot should show lines running straight up the image (see Figure 3) as all the fibres have been scrunched onto the same wavelength scale. See Section 3.6 if the reduced arc doesn't look like this.

It is also worth examining the reduced flat field frame and at least some of the object frames to confirm that the data reduction has proceeded successfully.

2.9 Restarting the data reduction system

All information about the progress of the data reduction is contained in the reduced files themselves. Thus if a data reduction session is interrupted (or the system crashes) drcontrol can be restarted, and the **SETUP** button used to pick up things exactly as they were. It will know which files have been reduced and be able to reduce any files that have not. However, in some circumstances this may not be the case, in which case it may be required to restart the data reduction process from scratch.

To repeat a data reduction session completely from scratch, redoing everything, delete all the `*im.sdf`, `*ex.sdf`, `*red.sdf/fits`, and `*t1m.sdf` files, and then restart drcontrol.

2.10 Cleaning up

2dfdr is extremely disc-space hungry. Many temporary and intermediate-stage files are generated in the reduction, and not all are deleted at the end of a reduction. In general, you will want to keep all `*red.sdf/fits` (your reduced data), and `*t1m.sdf`, `arclist*`, `fibpos*` files (which allow rereduction without refitting the tramlines). All other generated files (`_*.sdf`, `*im.sdf/fits`, `*ex.sdf/fits`, `t???.sdf/fits`, `background.sdf`, `corr_temp.sdf`, `fitg_iterations`) can be deleted.

3 The Data Reduction Process in More Detail

3.1 File Name Conventions

The automatic data reduction depends on the use of a file naming convention in which the name consists of a root name that is the same for all files. This is followed by a four-digit integer run number. Raw data from the AAT conforms to this convention with names of the form `13apr0001.fits`, `13apr0002.fits` etc². Data from the archive also conforms to the convention though the names are changed to `run0001.ft`s, etc.

It is possible to reduce individual files that do not conform to the naming convention. They can be loaded into the system using the **Reduce** item in the **Commands** menu. However such files cannot form part of the automatic reduction of a sequence of files, unless they are renamed to conform to the other files in the sequence.

The data reduction system adds suffixes to the file names for the results of each stage in the reduction process. Thus reducing file `run0001.sdf` would result in the following files:

- `run0001im.sdf` --- This is the first step in the reduction process and represents the raw image after the bias field and dark field (if any) have been subtracted, and it has been divided by the full (long slit) frame flat field (*not* a fibre flat field).
- `run0001t1m.sdf` --- The tram-line map; One of these is generated from each flat-field frame reduced.
- `run0001ex.sdf` --- This is the result after the tram line map has been used to extract the fibre information from the `*im` file.
- `run0001red.sdf` --- The final reduced file, derived from the `*ex` file by wavelength and throughput calibration followed by sky subtraction.

The `*red.sdf` file is the final result of the reduction process. The other files can be deleted if necessary after the reduction has completed.

3.2 Calibration Files

The system creates a number of calibration group files on start up.

² For data taken with the old CCD controllers prior to February 2004, the data have the form `13apr0001.sdf`, `13apr0002.sdf` etc. (i.e. these are in NDF format rather than FITS).

Group File	Description	Raw Data Class	Reduced Class	File Suffix
_BIASGROUP	Bias images	BIAS	BIASRED	red
_DARKGROUP	Dark frames	DARK	DARKRED	red
_LFLATGROUP	Long slit flat field frames	LFLAT	LFLATRED	red
_MFLATGROUP	Fibre flat field frames	MFFFF	MFSFFF	red
_WAVEGROUP	Wavelength calibration images	MFARC	MFSARC	red
_THPUTGROUP	Fibre throughput functions	MFSKY	MFSSKY	red
_TLMGROUP	Tramline maps	Any	Any	tlm

Each group file contains pointers to reduced calibration files of the given type. When the **Setup Automatic Reduction** panel is completed all calibration files that were found are entered into the appropriate group files. During reduction whenever a calibration exposure is reduced an entry is made for it in the appropriate group file.

At each stage in reduction when a calibration file is required, the corresponding group file is searched for a matching file, i.e. one with the same CCD and spectrograph settings. If there is more than one matching file the closest in time is chosen. This works provided calibration files are reduced before those files that will need the calibration data. In automatic reduction the correct sequence is chosen based on the class of the file to ensure calibration data are available when needed.

The **Show History** button in the **Data** tabbed page or the **Show History...** in the **Commands** menu can be used to show the calibration files that were used to reduce a selected file.

3.3 Tramline Maps

A crucial part of the reduction is the generation of a tram-line map which tracks the positions of the fibre spectra on the CCD.

The 2dF spectrographs have considerable distortion, and the tram-lines can be quite curved, especially near the edge of the frame. Currently 2dfdr determines the detailed curvatures for the 2dF tramline map using a rather complex algorithm, which incorporates the full optical model for 2dF and ray traces from the slit to the CCD to predict image positions on the CCD. Four “fibre position” files that list the positions of the fibres on each slit block are also used. See Section 3.3.2

For the other instruments, a much simpler algorithm is used. This algorithm searches for peaks along the centre of the image, adds a curvature based on a simple radial distortion model and then rotates to match the data.

A new tramline map is created from the first file to be reduced in each session. This is used for all subsequent files with the same spectrograph settings. Although a tramline map can be created from any data type, the best results will normally be obtained from a fibre flat field because of its high signal-to-noise. A twilight sky exposure, if available, is also a good

choice. When reducing a new data set for the first time, the automatic reduction always reduces the flat fields first.

3.3.1 Plotting the Tramline Map

Use the **Plot Tram Map...** item in the **Commands** menu to test whether the tramline map is a good match to the data. This will plot the tramline map overlaid on the data from which it was generated. The plot can be zoomed in or out with the **Z** or **O** keys on the keyboard (the plot must be zoomed several times to clearly view individual fibres). Use the **P** key to pan to the centre of the cursor position. The **Quit** button or **Q** key quits the display and allows data reduction to continue.

It is also possible to plot the tram-line map overlaid on the data during the reduction by switching on the **Plot Tram Map** check box in the **Extract** tabbed page. If set to **YES**, the plot is done twice during the course of each reduction, once with the initial tramline map, and a second time after adjusting the map in shift and rotation to match the data. If the **FLAT ONLY** option is chosen, the plotting only occurs for flat fields.

After zooming several times the plot should look like that in [Figure 2](#). If the tramlines don't correctly overlay the data then there are a number of possibilities.

- For 2dF data, a new fibre position file may be needed (see below).
- If the tramlines are poor in certain regions of the image, this may be a result of poor signal-to-noise data at some wavelengths, or excess noise in the data (e.g. due to cosmic rays). The software performs a final correction to the tramline map to match it to the data using a surface fit of polynomials. If this final fit is failing, the **Fit Tram Map to Data** check box in the **Extract** tabbed page can be used to turn it off. Alternatively, better results may be obtained using a different frame (occasionally the object data will work better than a flat field, because of a more uniform distribution of light as a function of wavelength).
- The grating or wavelength information in the header may be incorrect, which will change the tramline pattern slightly (see [Section 4.1](#)).

To re-generate the tramline map it is necessary to exit the system, delete any `*t1m.sdf` files, and restart.

3.3.2 Creating a New Fibre Position File (2dF data only)

If it is not possible to get a good tramline match for 2dF data, it is likely that the fibre position file (which lists the positions of the fibres on the slit) is not valid. The most likely cause of this is that the **Find Fibres...** command has not been run, or fibres have been mis-identified in the process of running **Find Fibres...**. It is also possible that the slit assembly has been modified since the file was created, or perhaps a grating change has changed the positions of the fibres on the CCD sufficiently to alter their apparent spacings. There are four fibre position files named as follows:

```
fibposa0.dat --- Spectrograph A (1), Field Plate 0
fibposa1.dat --- Spectrograph A (1), Field Plate 1
fibposb0.dat --- Spectrograph B (2), Field Plate 0
fibposb1.dat --- Spectrograph B (2), Field Plate 1
```

A new fibre position file straightforwardly can be created from the data. Use a well-exposed flat field covering all the fibres. Use the **Find Fibres...** item in the **Commands** menu. Select

the raw flat field data frame. The positions of the peaks will be located and used to generate a new fibre position file. A tramline map will then be generated from this file and a display of this overlaid on the data will be presented in the **Diagnostic Plots** window. Note that at this point the tram-line map will not have been corrected for rotation so it may not overlay the data perfectly. This plot should be carefully examined to check that the fibre numbering looks correct (use the **Z** key to zoom the plot, and the **Next** and **Previous** buttons to step up and down the chip).

Each tramline is numbered, in order 1-200 (in the case of 2dF data). If any fibres are known to be broken, they will have an asterisk displayed beside the fibre number. Positions corresponding to broken fibres will generally be dark, and so confirming that any broken fibres coincide with tramlines that have an asterisk is a good way to check that the tramlines are properly ordered (note, however, that this is not always the case, and broken fibres can sometimes appear as bright as normal fibres, depending on where and how they were broken). Another check that the fibre numbering is correct is to look at the gaps between each block of 10 fibres (i.e. between fibres 10 and 11, 20 and 21 etc). Due to the manufacture of the slit assembly, these gaps are usually slightly larger than the gaps between other fibres. If any problems in fibre numbering are visible on the display, fibres can be deleted or added interactively. To delete a fibre place the cursor on the fibre and press the **D** key on the keyboard. To add a fibre place the cursor on a point through which the tramline should pass and press the **A** key (it is advisable to have the plot highly zoomed for accuracy here).

If more than 200 fibres are found only the first 200 are plotted. Fibres beyond 200 can still be deleted by placing the cursor at the expected position of the next fibre beyond 200 and using the **D** key. Alternatively deleting a fibre number below 200 will cause them to be plotted. As fibres are added or deleted, the current number of fibres will be shown in the DREXEC message window. Click on the **QUIT** button in the plot window when the fibre numbering is correct (at this point there should be 200). If there are 200 entries at this point the fibre positions will be written to the appropriate file (fibposa0.dat etc.). If there are not 200 entries it will be written to a temporary file with the name `fibpos_temp.dat`.

Problems may arise if the data are incorrectly positioned on the CCD such that some fibres are off the chip area. Fibres can be added by hand to either the bottom or top of the find-fibres display until the correct number is obtained. It does not matter if these positions are off the chip. As a last resort the fibre position `fibpos_temp.dat` file should be edited (it is just a text file listing the fibre positions) to add additional entries at one or other end to bring the total number to 200 and then rename it appropriately (e.g. to `fibposa0.dat`).

3.3.3 Reducing the Flat Field

At this point, the positions of the tram-lines should match the spectra in the fibre flat field at the central wavelength, but not necessarily elsewhere. At this stage, the tram-line map is compared with the actual data in the fibre flat field and further adjusted until it perfectly matches the data. This is done in two steps.

- 1) A shift and rotation correction is applied to the tram-line map. This is obtained by taking 20 equally spaced cuts across the image in the y direction, locating the data peaks in each cut using a peak-finding algorithm, and then determining the shift and rotation needed to minimize the difference between the measured peaks and the positions in the tram-line map.
- 2) A final correction is applied by measuring the deviation of the data from the tram-line map over a 10 by 10 grid of regions across the CCD. The deviations are measured using

the same process for finding and matching the peaks described above. A set of polynomials is then fitted to the deviations along each tram-line and linear interpolation between these is used to correct each tram-line. After this final correction the tram-lines match the data to typically 0.05 pixels or better.

The final correction requires good data across the CCD to work well. In some cases this is not available, for example when working in the far blue. In this case, this step is best omitted, by turning off the **Fit Tram Map to Data** check box in the **Extract** tabbed page³.

3.3.4 Tramline Maps with Other Files

When data files other than fibre flat fields are reduced the only adjustment to the tramline map is, for 2dF, a **Rotate/Shift to Match** correction to bring it into alignment with the data. This correction is necessary because flexure in the spectrographs causes the tramline pattern to move across the CCD slightly as the telescope tracks. 6dF and SPIRAL users should not make any correction.

3.4 Fibre Extraction

The fibre extraction process uses the tram-line map and the image to extract the spectrum for each of the 200 fibres. The simplest method is the **TRAM** option in the **Extract** parameters, which sums the pixels around the tram-line over a width slightly less than the spacing of the tram-lines.

An alternative method is the **FIT** option, which attempts an optimal extraction based on fitting profiles determined from a flat field frame. This should give somewhat better signal-to-noise than the **TRAM** extraction, and should better handle the overlap between adjacent fibres, since the fit is done simultaneously to the two fibres on either side of the one being extracted. **FIT** extraction is much slower than **TRAM** extraction. A flat-field must be reduced using the **FIT** method before any other frame, to provide the profiles needed for the extraction.

Fibre extraction involves three steps:

- 1) The background level (mostly due to scattered light) is subtracted from the data.
- 2) In the case of **FIT** extraction the profiles to be used for extraction are determined from a fibre flat-field frame by fitting overlapping Gaussians. The profile information is stored with the tram-line map derived from the flat-field for subsequent use during the extraction of the flat-field and other frames.
- 3) In the **FIT** option the actual extraction is performed by least-squares fitting of the profile to the data simultaneously with the profiles on either side, thus allowing for contamination from the overlap of adjacent fibres. In **TRAM** extraction the data are simply summed along the tram-lines using a width slightly smaller than the inter-fibre spacing.

These steps are now described in more detail.

3.4.1 Background Subtraction

The software can perform a subtraction of background scattered light before doing the extraction. This is turned on using the **Subtract Scattered Light** option in the **Extract**

³ This button does not exist for 6dF.

tabbed page. This option is **recommended** when **FIT** extraction is used, and is optional with **TRAM** extraction.

The background is determined by fitting a function through the “dead” fibres in the image. When a flat field (class MFFFF) is reduced the list of dead fibres is taken from the header of the image, and each is checked to see if it has signal in it (as some broken fibres may still transmit light). The dead fibres actually found are written to a file (deadfibresa0.dat, deadfibresb0.dat etc. - one for each of the four slit assemblies). This text file can be edited to add or remove fibres. Once such a file is present in the directory it will be used for all subsequent reductions. At least 2 dead fibres are required for scattered light subtraction to work (in which case it just fits a line rather than a quadratic), with 3 being the minimum to do the full quadratic fit. Obviously, better results will be obtained if more dead fibres are available, and the results also depend on the spacing of the dead fibres. 6dF uses the fixed gaps in the slit block, see the 6dF section for more details.

The function fit to the dead fibres is basically a quadratic with a fall-off at each end, forced to be convex upwards. This background model was empirically determined by study of many typical 2dF background profiles. The function is fit to each CCD column by first fitting a polynomial to give an initial approximation and then using a modified Levenberg-Marquardt algorithm to fit the full function. The resulting background is then smoothed in the spectral direction by median-filtering followed by a cubic spline fit, before subtracting from the data.

3.4.2 Fitting Profiles

For **FIT** extraction the profile-fitting routine fits 200 overlapping Gaussians to the 200 fibre profiles in each column of the fibre flat-field image. It is assumed that the width of the Gaussians varies smoothly across the image and can thus be described by a polynomial. Since the background has already been removed, the only independent parameters for each Gaussian profile are the height and a centre position offset. The full fit is done for about 20 columns spaced across the CCD. The profile parameters are then interpolated over the whole image using cubic spline interpolation. The output is the parameters describing the Gaussian position and sigma for each of the 200 fibres in each CCD column. These are stored with the tram-line map data in the *t1m file.

3.4.3 Extracting Spectra

In the **FIT** extraction method spectra are extracted from the images by fitting the profiles, determined as described above, to the image data. Since the background has already been subtracted, the position of the profile centre is determined in the tram-line matching, and the sigma of the Gaussian has been determined in the profile-fitting stage, the only parameter to be determined for each fibre profile in each CCD column is the height of the Gaussian which gives the corresponding point in the spectrum. A simultaneous fit of each fibre and its neighbours on either side is done, which minimizes any contamination of a spectrum from its neighbours.

Typically, therefore 15 to 16 pixels of data along a column are fitted with three overlapping Gaussians, where the only free parameters are the three peak heights of the Gaussians. A variance weighted linear least-squares fit is performed, with only the peak height of the central fibre actually being used to determine the value of the spectrum.

TRAM extraction is a much simpler process (and therefore quicker), but is more sensitive to contamination from adjacent overlapping spectra. This method simply sums the data along the tram-lines using a width approximately equal to the inter fibre spacing. For the best results it is recommended to use **FIT** extraction.

3.4.4 Plotting Fits

The **Plot Fits** option turns on a plot of the fits to the data for selected columns for the background subtraction, and the fit extraction.

3.4.5 Cosmic Ray Rejection

Cosmic rays are rejected during the extraction process on the basis of the spatial profile across the fibre. The spatial profile for a single wavelength channel is compared with the median profile over a block of pixels on either side of the current pixel. If it differs by more than a threshold value (the default is 20 sigma) the pixel is rejected and flagged as bad in the resulting spectrum.

In principle such a procedure based on only the spatial profile should be insensitive to the spectral structure of the data and there should be no danger of it mistaking a strong emission line for a cosmic ray. However, in practice this is not true with 2dF data for two reasons:

- The overlap between the fibres means that the wings of the profile will change when a strong emission line is present in one fibre but not in the adjacent fibres. This problem should not occur with FIT extraction.
- The image quality is not perfect, and images of a bright emission line are often seen which are elongated at a 45 degree angle. In such cases the spatial profile does change across the line.

For these reasons the default rejection threshold has been set at a fairly conservative value which ensures that no real features will be rejected as cosmic rays in typical data. However, it means that only the worst cosmic rays/spurions are removed, and some smaller ones will still get through.

In very high signal-to-noise data it may be necessary to increase the threshold further or turn off cosmic ray rejection entirely. For this reason cosmic ray rejection is automatically turned off when flat fields and arcs are extracted. The best way to remove cosmic rays is by combining object spectra from separate frames after reduction, using the **Combine Reduced Frames** option with 2dfdr. For this reason, it is recommended to take at least three exposures for all configurations, and to turn off cosmic ray rejection during the reduction of each individual exposure.

3.4.6 Fibre Overlap

The fibre spectra are packed very close together on the detector. The design specification was that they would overlap at about the 1% level on the profile. However, the actual situation is worse than this, and in some early data it is much worse due to poor focus. Some data are also affected by halation⁴ giving extended wings on the profile. This means that there is often significant contamination of a fibre spectrum by light from the adjacent fibre. This is

⁴ Small amounts of “stuff” can condense on the inside of the camera window. This tends to increase over time, and is worse in spectrograph 2 of 2dF. The solution is to warm up and then cool down the dewer. The condensate causes a weak broad scattering halo - halation.

particularly bad when there is a bright object in the fibre adjacent to a fainter one. **TRAM** extraction can be seriously affected by contamination from adjacent fibres. The problem is much less serious with **FIT** extraction.

3.5 Dividing by Fibre Flat Field

At this point the extracted spectra can be divided by a normalized flat field frame made from the spectra extracted from a continuum lamp exposure. Flat fielding in this way is not ideal, as the spectrograph flexure means that the flat field spectra are extracted from slightly different pixels from those being calibrated. However, it is still found to be useful in removing large-scale flat field structure (the 2dF Galaxy Redshift Survey uses this option). A method of taking full chip flat fields that would allow better removal of pixel-to-pixel sensitivity variations was originally planned but was never implemented in 2dF. Dividing a MFFFF frame by a median-filtered (e.g. 1 spatial x 11 spectral pixel) version of itself will give a reasonable flat field, but the rms QE variation for 2dF is <1%, so many frames are needed and the gain is small. A long-slit calibration facility will be available with AAOmega.

The fibre flat field is created from an extracted flat field frame. The extracted fibres are first averaged to generate a mean flat field. This is used to divide the individual fibre flat field spectra in order to remove the lamp response. Each divided flat field spectrum is then normalized so that its median is equal to 1. One source of systematic errors in this process is that if there is any tilt in the slit causing small wavelength offsets (typically of order a few to 10 pixels), the fibre flat field spectra will not have exactly the same responses in pixel space. Any structure in the spectrum of the flat field lamp (either bumps, notches or gradients) will then leave systematic residuals in the final flat field spectrum. These can be of the order 1-2%.

A solution to this has recently (Nov 2004) been implemented. Once a flat field frame has been reduced, an arc should be reduced (as normal), then the flat field frame re-reduced. The flat field will then be crunched (i.e. re-sampled) onto the correct wavelength scale, averaged, and then the average spectrum “un-crunched” onto the original pixel scale before dividing the individual fibre flat fields. This results in a fibre flat field with the correct pixel-to-pixel response, but also with no large-scale systematic errors due to lamp response variations. The automated reduction procedure will automatically re-reduce the flat fields after the arcs have been reduced.

3.6 Wavelength Calibration

The data reduction system performs an approximate wavelength calibration using the information from the spectrograph optical model, the central wavelength in the file header, and assuming the fibres in the slit are in a line (which is not really true). It then refines this using data from an arc lamp exposure. Lines are found in the arc lamp spectrum using an algorithm that searches for peaks. A peak here is defined as a pixel at which the signal falls significantly (at least 2 sigma) on either side. The central position of each line is determined by fitting a parabola through the three points around the peak.

2dF includes CuAr, helium, and FeAr lamps, which can be used in combination. For each lamp and lamp combination there is a file (with extension `.arc`) that contains the wavelengths in angstroms and approximate intensities in relative units of the lines produced by the lamp(s). The files are named for the lamp(s), e.g. `cuar.arc` for the CuAr lamp, `helium.arc` for the helium, and `hecuar.arc` for the CuAr and helium combination. The file that is used

depends on the value of the LAMPNAME header keyword in the arc data file. Changing this key word enables user specified line lists to be used.

The line wavelengths and intensities in this region of the spectrum are read from the arc file for the appropriate lamp(s). The weaker lines are removed from either the list of measured positions or the list of actual wavelengths until there are roughly equal numbers of lines in both lists. Finally, the shifts are determined which bring the measured positions into registration with the expected positions from the true wavelengths.

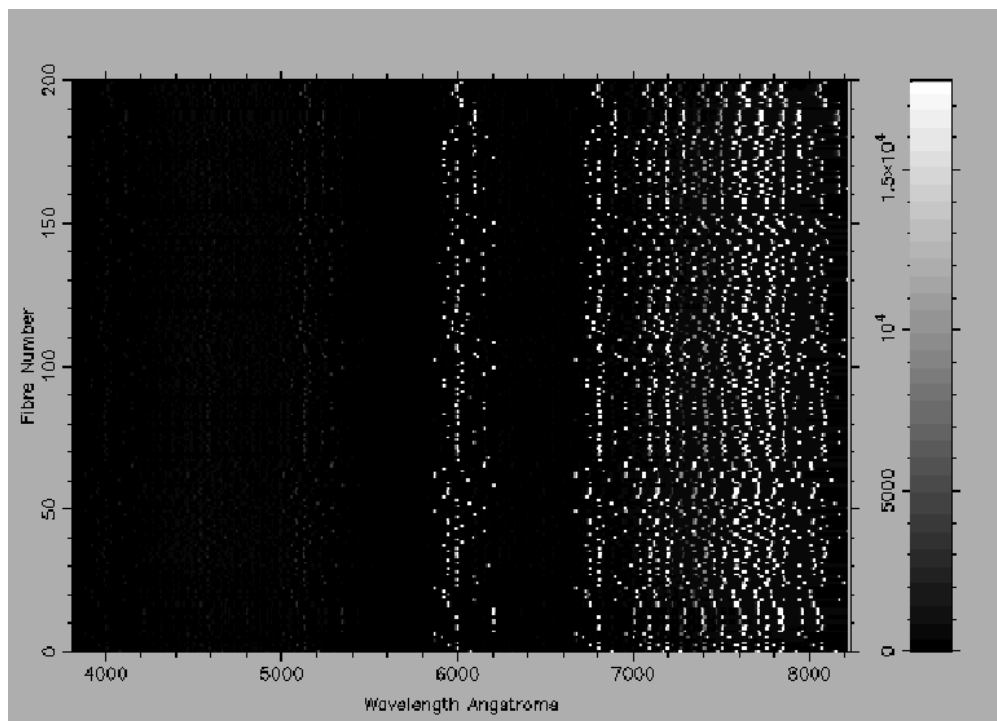


Figure 4: Appearance of an incorrectly reduced arc exposure. The arc lines in different fibres do not line up. Such a result is usually caused by incorrect wavelength or grating information in the header, or (as in this example) by use of the wrong arc line list. Compare with Figure 3.

A cubic fit is then performed to the predicted and measured wavelengths of all the “good” lines for each fibre. A good line is one that is not a blend (i.e. there is no nearby line in the line list), is not too wide (which usually indicates saturation), and is not too weak. The fit is then improved, if necessary, by removing up to four points with the largest deviation from the fit. This fit is then used to refine the wavelengths and the arc spectrum is scrunched onto the new wavelength scale (i.e. rebinned onto a linear wavelength scale). This procedure is repeated for each fibre spectrum in the wavelength calibration observation, producing a set of polynomial coefficients for each fibre relating the initial approximate wavelength calibration to the true wavelength scale. This information is stored in the final file with the reduced calibration lamp spectra. The details of the arc fit to each fibre are also output to a text file with a name of the form `arclistnnn.dat` for run number `nnn`, e.g. `arclist021.dat` for the fit to arc spectra in run 21.

In a plot of the reduced arc the lines should be straight across all 200 fibres, and the wavelengths should be correct; see Figure 3. If wavelength calibration is bad, the most likely reason is that the central wavelength specified in the header is not close enough to the true value for the software to correctly match the lines. This can be checked by comparing the

raw arc data with an arc map. Other things that could cause problems are incorrect grating information in the header.

When other files are reduced the calibration from the best matching arc exposure will be used to set the wavelength scale. For these other files, the data are rebinned onto a linear wavelength scale as described above, but instead of using the initial approximate wavelength scale, the wavelength scale is corrected using the polynomial fits from a wavelength calibration file, to give the true wavelength scale.

If there are problems getting a good arc fit, it may be possible to improve things by editing the arc file to remove lines which are causing problems. An arc file in the working directory will be used in preference to one of the same name in the standard 2dfdr directory⁵.

Note that although the arcs are used to determine the transformation from pixel to wavelength coordinates, the actual range in wavelength that the data is scrunched to is defined by the central wavelength in the FITS header of the data frames (which will be the same for all the data taken with a particular spectrograph setup). This has the advantage of allowing simple combining of data in pixel space, amongst other things. Some bad pixels at the ends of the spectra are inevitable, because of imperfectly lined-up fibres, and slit curvature. But because there is some uncertainty in the encoder reading that gives the grating angle and the model that converts this to central wavelength, there are often a number of pixels (typically 10-20) at one end of **all** the data which are bad due to a slightly incorrect central wavelength. Editing the LAMBDA FITS header item to give the exact central wavelength and re-reducing the data will fix this problem if this is an issue (the wavelength scale scrunched on to is defined when the flat field is reduced, so all frames need to be re-reduced, including the flat fields).

3.7 Fibre Throughput Calibration

Before sky subtraction can be done, it is necessary to correct for fibre-to-fibre differences in throughput and to normalize all of the fibres to the same level. There are three methods available for fibre throughput calibration:

3.7.1 Offset Sky Method

Offsky

In this method offset-sky exposures are used to calibrate the relative fibre throughput. These are exposures taken with the same fibre configuration as the target field, but with the telescope offset from the nominal field centre, so that the fibres are (mostly) looking at sky. In practice, it is quite common for some fibres to land on objects in the offset position, so normally one takes at least three offset-sky exposures at different position offsets. Twilight sky exposures are also useful for throughput calibration, but it's not normally possible to acquire these for every fibre configuration used during a night. Note that while in uncrowded fields one normally offsets by 20--30 arcsec, in crowded fields (e.g. centre of LMC), one may need to offset by as much as several degrees.

The offset-sky or twilight-sky exposures (class MFSKY) are processed in the same way as target field observation until wavelength calibration of the extracted spectra. At this stage the spectra are combined with those from any other offset-sky frames for the same instrument configuration. The frames are combined as described in Section 3.9, but without continuum

⁵ For 6dF, the initial wavelength solution can be edited as described below.

adjustment and flux weighting. Therefore it is not necessary to manually combine the offset sky files before running the data reduction system. When reducing an offset sky file the system automatically checks if it matches any previous files, if so all the matching files are combined and a throughput map derived from the combined file. This throughput map is stored with the reduced file. When calibrating an object frame the system will choose the matching throughput map combined from the largest number of frames. The reduced file for the offset sky frames contains the combined throughput map, but the data array is only that for the single frame (this allows it to be combined with subsequent frames if necessary). The combined sky is contained in a temporary file with the name `COMBINED.sdf`.

The relative throughput for each fibre is obtained from the combined offset-sky spectra as the mean signal in the fibre, divided by the median over all fibres.

3.7.2 Sky Lines Methods

Skylines, *Skylines(kgb)*

With these methods, the relative intensities of the skylines in the object data frame are used to determine the relative fibre throughput. This method saves time, as no offset-sky observations are required. However, it can only be used for spectral regions with skylines, and will not work in particular for high dispersion data in the blue. The 2dfdr implementation makes use of all skylines present. The two different versions of the algorithm are called *Skylines* and *Skylines(kgb)* (the second of these written by Karl Glazebrook). These works as follows:

- The median sky spectrum is calculated from the median of all the sky spectra normalized by their mean flux.
- In the *Skylines* method the differential of every object and sky fibre and the median sky spectrum is taken. In the *skylines(kgb)* method each of these spectra are continuum subtracted, using a boxcar median smoothing with a 201 pixel box to define the continuum.
- A robust least-squares fit is performed of the counts in the differential or continuum subtracted data fibres versus the counts in the differential or continuum subtracted median sky. Assuming that the sky is the dominant source of emission, the slope of this fit gives the fibre throughput. The robust fit is especially important when dealing with faint objects.

3.7.3 Sky Flux Methods

Skyflux(med), *Skyflux(corr)*

The **skyflux** throughput calibration methods are based on similar ideas to those of the skylines methods. The strength of the night sky emission lines are used to normalize the fibre throughputs. They differ from the skylines methods in that they determine the fibre throughputs from the total flux in a number of sky lines, rather than comparing sky emission on a pixel-to-pixel basis. This has the advantage of correcting (to first order) for any variations in the spectral PSF across the detector. When using the skylines methods, these PSF variations can cause systematic errors in throughput calibration (and therefore sky subtraction), which vary across the detector. The new skyflux algorithms were designed to be implemented in cases where a number of night sky lines were present, particularly when using 2dF at low resolution, e.g. with the 300B gratings. There are two algorithms, *skyflux(med)* and *skyflux(corr)*. *Skyflux(med)* works as follows:

- Every object and sky fibre is continuum subtracted using a boxcar median smoothing with a 201-pixel box (as for skylines).
- The total flux in each of a number of sky emission lines is found, summing over a box of half width approximately twice the FWHM of the features. The default night sky emission lines used are O I $\lambda 5577$, NaD $\lambda 5892.5$, O I $\lambda 6300$, O I $\lambda 6363$ and OH $\lambda 6832.5$.
- The flux in each emission line is used to derive a relative throughput value (relative to the median flux in the particular emission line). For five emission lines this would result in five independent throughput estimates per fibre.
- The final throughput for each fibre is determined as the median of the throughput values found for each emission line.

The skyflux(med) algorithm is robust and should work even if only one sky emission line is present in the spectrum (although if that line contains bad pixels the algorithm could fail).

The skyflux(corr) method is similar to skyflux(med), but has the advantage of being flux weighted, so that the throughput values should have reduced scatter (skyflux(med) gives equal weight to all night sky emission lines). The skyflux(corr) algorithm works as follows:

- Every object and sky fibre is continuum subtracted using a boxcar median smoothing with a 201 pixel box (as for skyflux(med)).
- The total flux in each of a number of sky emission lines is found, summing over a box of halfwidth approximately twice the FWHM of the features. The default night sky emission lines used are O I $\lambda 5577$, NaD $\lambda 5892.5$, O I $\lambda 6300$, O I $\lambda 6363$ and OH $\lambda 6832.5$ (as for skyflux(med)).
- A robust linear fit (forced to go through the origin) is carried out between the measured sky fluxes in each line (e.g. the 200 fluxes for O I $\lambda 5577$ are fitted against the 200 fluxes for O I $\lambda 6300$, and for every other combination of lines).
- Any outliers from the fits (due to CR contamination or strong emission lines in the targets) are rescaled to the best-fit line.
- The flux in all the used lines is summed for each fibre, and a throughput value is derived from this (normalized to the median flux).

The skyflux(corr) method only works when at least two night sky emission lines are present in the data, and preferably more. With only one or two lines skyflux(med) will be just as accurate. The wavelengths of the night sky emission lines used are stored in the file `skylines.dat`, which can be found in the **DRCONTROL_DIR** directory. This can be copied into the current working directory and edited to add or remove lines. 2dfdr will look first in the current working directory and then in the **DRCONTROL_DIR** directory for the `skylines.dat` file.

3.7.4 Finally ...

The throughput derived by either of the above methods is then applied to the data by dividing each spectrum by its corresponding fibre throughput.

3.8 Sky Subtraction

The final step in data processing is to sky-subtract. Any fibre configuration normally contains a number of fibres (typically 10-20) assigned to sky positions. A combined sky spectrum is made by taking the median of the corresponding pixels in each of the normalized sky fibres (see the previous section). The median is used so the combined sky is insensitive against any

sky fibres accidentally contaminated by sources, or by cosmic ray spikes. For the purposes of calculating the sky subtraction accuracy only, the two brightest sky fibres are rejected.

This combined sky spectrum is then subtracted from each fibre spectrum (including sky fibres). Although sky subtraction is simple in principle, good results are crucially dependent on effective throughput calibration, wavelength calibration and background subtraction. The continuum sky subtraction accuracy, measured from the residual light in the sky fibres after sky subtraction, is typically 2-3% of the sky level. Better sky subtraction is possible using techniques such as beam switching and “nod & shuffle”, but these have other limitations such as decreasing the number of available objects and/or reducing the amount of on-source exposure time.

3.9 Combining Reduced Spectra

All of the processing steps described above are applied to individual frames. `2dfdr` is also able to combine frames observed on the same field, with optimal signal-to-noise and with cosmic ray cleaning. The basic algorithm is modelled on the `crreject` algorithm in the IRAF `imcombine` package:

- An initial estimate of the typical data value in each pixel is made, by taking the median of that pixel for all the frames. The median is used because it is robust against cosmic ray events in a few frames. If there are only two runs, the minimum is used instead of the median, since cosmic ray events are positive, and it is very unlikely that a cosmic ray will occur in both pixels.
- Next, cosmic rays are flagged by comparing the data value in each frame with the median estimate. If the value exceeds it by **n** sigma and/or a fraction **m** as set in the **Combine** tabbed page, then the pixel is flagged as a cosmic ray. Statistics are reported to the user about the percentage of cosmic rays rejected, which should be of order 1-2% per hour with the TEK CCDs.
- Regions identified as affected by cosmic rays are “grown” by flagging adjacent pixels (± 2 pixels). This handles energy spill over and artificial smoothing of cosmic ray events by previous data reduction steps.
- The final data value is taken as the mean of the non-flagged data values, weighted optimally by the inverse variance. Once cosmic rays have been rejected, the mean is robust, and gives better signal-to-noise than, for example, the median; it also allows optimal variance weighting. Pixels masked out as cosmic rays effectively are “filled in” from the good pixels on other frames.
- Finally, the final data value is multiplied by the number of frames so that it is equivalent to a “summed” image rather than an “average” image. This is purely a choice of convention. The result is close to what would be obtained by just summing the frames, if the data had no cosmic rays.
- Note that the data variance is propagated correctly to the final combined frame at all steps in this procedure.

This algorithm was tested extensively by combining data with and without cosmic ray rejection and examining the difference images; to ensure that only true cosmic ray events were rejected (and not, for example, real spectral features!). The algorithm works well because the expected variance can be calculated very accurately knowing the detector read noise and gain, and because the sky background has already been subtracted during previous reductions. However, it was found necessary to add two user selectable options to cope with particular common problems.

3.9.1 Continuum Level Adjustment

It was commonly found with early 2dF data that the object spectra showed 10-20% spectral shape variations between consecutive runs. This was traced to the Atmospheric Dispersion Corrector (ADC) not being properly calibrated. For data taken previous to 31 August 1999 (when the ADC was fixed), 2dfdr now has an empirical fix for this problem, which is to adjust the continuum level of each spectrum before cosmic ray rejection. A heavily smoothed version of each spectrum in the series of frames is made by applying a box-car median filter (with a width of 101 pixels). This estimates the spectrum continuum level in a way which varies slowly with wavelength and is robust against cosmic rays and real spectral features.

Next, the mean smoothed spectrum is subtracted from the array of smoothed spectra to make an array of smoothed differences, which is then subtracted from the data spectra to align them in continuum level with each other. This procedure takes out the small variations well enough to match the spectra to better than the noise level. This in turn allows the cosmic ray algorithm to only identify true cosmic ray events. This option is on by default, but can be turned off. Even for data taken after 31 August 1999, it is probably worth using. See Section 5.4.2.

3.9.2 Flux Weighting Option

When data are taken in strongly varying seeing, atmospheric transmission (e.g. large variations in airmass) or cloud cover conditions, or when separate frames have different exposure times, some frames may have a lot less flux in **all** their spectra than other frames. To combine such data optimally, it is necessary to assign weights to the data proportional to the flux in it (otherwise noise will be added to the data). There is thus an option provided in 2dfdr combine for **flux weighting**.

There are two different modes of flux weighting: **FRAMES** and **OBJECTS**.

3.9.2.1 FRAMES flux weighting

The key step is to robustly calculate the flux weights. In old versions of 2dfdr (prior to Nov 2004) these were calculated for the brightest objects in each frame, and then applied to all objects. This algorithm for calculating flux weights worked as follows:

- First, smoothed versions of all the spectra in a frame are made using the same boxcar median filter (width 101 pixels) as for the continuum adjustment. This effectively eliminates contribution from cosmic rays.
- The flux in each of the smoothed object spectra in a frame is summed, and the sum of this over all frames is stored as an empirical “brightness parameter” for each object. The summed fluxes for each frame are then normalized (scaled so the first frame is unity) and result is stored as the flux weights for that object.
- The 5% of fibres containing the brightest objects is found by sorting the list of total fluxes.
- The global frame-to-frame flux weights for all of the spectra are formed by averaging the individual values calculated for the brightest 5%.
- The global flux weights for the sequence of frames are then renormalized so the maximum weight is unity. This causes the final combined spectrum to be normalized as if all frames were taken in the best conditions (though the signal-to-noise is obviously worse).

By deriving the flux weights from only the brightest spectra, very accurate values for the relative brightness changes between frames are found. Because the weights are normalized before averaging to derive global weights, all the bright objects contribute equally and the result is not dominated by a single very bright object. The procedure is also robust against cosmic rays in individual frames.

The above algorithm was found to give spurious results in the case of low S/N data, where even the brightest fibres did not have enough signal to act a good estimators of the weights. For this reason a new algorithm has now been implemented (from Nov 2004) which compares the expected and measured counts to derive a median “zero-point” for each frame to be combined. This works as follows:

- First, smoothed versions of all the spectra in a frame are made using the same boxcar median filter (width 101 pixels) as for the continuum adjustment. This effectively eliminates contribution from cosmic rays.
- The source magnitudes (contained within the fibres extension of the data file, and supplied by the user in the configuration files) are extracted from the data frames.
- The flux in each of the smoothed object spectra in a frame is summed, and the sum of this over all frames is stored as an empirical “brightness parameter” for each object.
- The measured flux is compared to the expected flux (as derived from the source magnitude) to determine a zero-point for each fibre.
- A median of the fibre zero-points is taken to derive a frame zero-point.
- These zero-points are used determine the relative weights with the best frame given a weight of unity.

The final global flux weights are used throughout the combine algorithm described earlier. They are used to correctly scale individual frames for the determination of the initial median and N-sigma deviations during the cosmic ray rejection, and as weights for the final combination. The flux weighting algorithm was tested by taking real data and degrading it to simulate the effects of bad cloud or seeing.

3.9.2.2 OBJECTS flux weighting

In this case instead of using a single weight for each frame, each object has an individual weight. This method should be appropriate where variation in throughput across the field is suspected (e.g. due to varying acquisition/guiding errors). A similar process to that above is used where the object spectra are smoothed and a sum taken. However, this method then directly takes the sum of the smoothed frame as the weight (after normalization relative to other observations of the same object). These single object weights are less robust than the frames weights, so may not be appropriate for very faint targets, where the weights may have large errors.

It is recommended that the flux weighting option be used for data taken in variable conditions: the signal-to-noise will be increased.

NOTES:

- Flux weighting is not always appropriate: for example, if all objects have the same brightness and are very faint, or if they are pure emission-line objects. The 2dfdr default is to not have flux weighting.
- Flux weighting and continuum adjustment can be used together, and the errors will be propagated correctly.

- Without flux weighting, the combine algorithm does not scale by exposure time, so when combining frames of different exposure times, the flux weighting option should be used; it will automatically take into account the different scaling.

3.9.3 Combining by object name

A final improvement to the combining algorithm (as of March 2004) is that instead of simply combining based on the fibre number in the reduced data frames (i.e. combine fibre 1 in frame 1 with fibre 1 in frame 2 etc.), the 2dfdr combine algorithm now combined data based on object name. This has a number of advantages:

- Multiple configurations of the same field can be combined together in the case where some, but not all objects are in common.
- Only sky (S) and program (P) fibres are combined. This includes cases in which a fibre has been disabled part way through the observation of a field, so that only the good data is combined.

This can result in final combined data frames in which there are more than 200 spectra, so that all objects are contained, whether they are contained within every frame or only a sub-set of the frames. The first 200 will be those from the first frame (including any unused/parked and sky fibres), while those from fibre 201 (in the case of 2dF) will be extra program (only) spectra from objects not present in the first frame. All the fibres extension information is properly propagated in this process and an extra array is added listing the actual exposure time (in seconds) for each spectrum. If the data combined are all from the same configuration there will be no difference between the new combining and the old fibre number combining (apart from that unused/parked fibres will have all their values set to zero).

3.10 Summary of Data Reduction Sequence

The sequence of data reduction for an object file is as follows:

Debiasing The mean of the bias strip is subtracted from the data, and the bias strip trimmed from the data frame. Then a variance array is derived from the data with values determined from photon statistics and readout noise. This is attached to the data file so that the variance can be propagated through subsequent steps in the processing. If a bias frame is available it is subtracted from the data (The bias frame already has the mean level of its bias strip removed).

Dark Subtraction If a dark frame is available it is subtracted, after scaling for the relative exposure times. Dark frames are not usually taken.

Flat Fielding If a long slit (full chip) flat field is available the data can be divided by the normalized flat field frame. For 2dF there is no way of taking a long slit flat field. This facility should be available for AAOmega.

The result of these initial stages is a reduced image file which is indicated by the suffix “im” appended to the file name.

Tramline Map Generation If a suitable tram line map is available it is matched with the data by determining the relative shift between the map positions and the peaks found in the data, for a series of cuts through the image. A robust straight line fit is performed to determine a shift and rotation angle and the tram-line map adjusted accordingly. If no suitable

tram-line map is available then one is generated by ray tracing through the optical model of the system for a range of wavelengths and slit positions and then performing surface fits to the resulting positions to derive both the tram-line map for each fibre and the wavelength of each pixel on each fibre.

Fibre Extraction Using the tram-line map and reduced image, this stage extracts the spectrum of each fibre. There are two possible methods. The TRAM method is a simple extraction, which simply sums the pixels along each fibre over a width equal to the distance between adjacent fibres. Some cosmic ray rejection is performed by comparing the spatial profile for the pixel with the median profile over a block of pixels. The FIT method performs an optimal extraction by fitting profiles determined from a flat-field frame.

The fibre extraction stage also adds an approximate wavelength calibration to the data based on the spectrograph optical model. The end result of this stage is the extracted file which is indicated by an ex suffix. This file contains the data in the form of a 200 by 1024 array giving the data for the 200 fibres.

Wavelength Calibration The data are rebinned onto a linear wavelength scale, which is the same for all fibres. If available, the wavelength shift and dispersion determined from a wavelength calibration lamp exposure are used. If no calibration is available the approximate wavelength scale from the optical model is used.

Sky Subtraction The data are first corrected for the relative fibre throughputs, based on a throughput map derived from the offset sky exposures or from the relative intensities of night skylines. The sky fibre spectra in the data frame are then combined and subtracted from each fibre.

Combining Reduced Runs Individual runs may then be combined optimally and with cosmic ray rejection, if desired.

4 2dF Data Headers and the 2dfinfo command

2dF data files contain two types of header information. A standard FITS header contains information on the telescope, CCD, spectrograph etc. However the information on the fibre configuration is contained in a special FIBRES extension in the NDF files. This contains information on the name, position, type etc. of the object allocated to each fibre. In addition reduced files contain an NDF History extension, which describes the reduction history of the data. For example, which data reduction steps were applied to it, and which calibration files were used. If the data is stored in FITS format then the above data is stored in FITS binary table extensions.

4.1 FITS Keywords used by 2dfdr

The following table contains a list of all the FITS header keywords used by 2dfdr:

FITS keyword	Description
RUN	Run number.
INSTRUME	Instrument in use (e.g. 2dF, 6dF etc.).
SPEED	CCD Readout speed name (e.g. Normal, Fast etc.).
WINDOW	CCD Readout window name.
SPECTID	Spectrograph ID.

GRATID	Grating ID (e.g. 300B, 600V etc.).
LAMBDAC	Nominal central wavelength.
ORDER	Order of spectrum (normally 1).
SOURCE	Plate number (0/1 for 2dF).
UTSTART	UT at start of exposure.
UTDATE	UT date.
METHOD	Control task control method (i.e. Normal or Shuffle).
SHIFT	Nod and shuffle shift (N&S observing only).
HARTMANA	Hartmann shutter A is open/closed.
HARTMANB	Hartmann shutter B is open/closed.
DETECTOR	CCD chip name.
GRATLPMM	Grating ruling Lines/mm.
GRATBLAZ	Grating is blaze to collimator (default) or camera.
DETECXE	Last column of detector.
DETECYE	Last row of detector.
EQUINOX	Equinox of Position, years A.D. (SPIRAL/LDSS only)
MEANRA	Right ascension (SPIRAL only)
MEANDEC	Declination (SPIRAL only)
EPOCH	Current Epoch, years A.D.
TEL_PA	Rotator position angle (SPIRAL only)
LAMPNAME	Calibration lamp name (only if in use).
EXPOSED	Integration time(seconds)
RO_NOISE	Readout noise (electrons)
RO_GAIN	Readout (inverse) gain (e-/ADU)
GRATSET	Grating setting (6dF)
GRATSLOT	Grating slot (6dF)
FIELDYB1	CCD on chip binning factor in Y (only if binned).
FIELDXB1	CCD on chip binning factor in X (only if binned).

Some of these keywords are only used with certain instruments (e.g. 6dF or SPIRAL), and so are not required for all datasets. Most are produced as standard in AAO data recording tasks.

4.2 Using the *2dfinfo* command

This header information can be accessed from the data reduction system using the **Show Header**, **Show Fibres** and **Show History** buttons, or equivalent items in the **Commands** menu.. However, it is sometimes more convenient to access this information without having to run up the data reduction system. The command **2dfinfo** has been provided for this purpose. It can be used in a number of ways as follows:

```
% 2dfinfo run0001.sdf fits
```

lists the FITS header of run0001.sdf.

```
% 2dfinfo run0001 fibres
```

lists the fibre configuration information for the same file (note that the `.sdf` extension is optional).

```
% 2dfinfo run0001red history
```

lists the reduction history of the reduced file run0001red.sdf.

It is also possible to request information for an individual fibre or an individual FITS keyword as follows:

```
% 2dinfo run0001 fibre 37
```

lists the information on fibre number 37.

```
% 2dinfo run0001 fits-item GRATID
```

lists the value of the fits header item GRATID (grating ID).

5 A Tour of the User Interface

5.1 The Menus

5.1.1 The File Menu

The **File** menu contains only one active command, which is the **Exit** command that is used to exit from the data reduction system.

Previous versions of 2dfdr also contained an **Open...** command that could be used to open a data file and add it to the list of files accessible through the **Data** tabbed page. In some versions of 2dfdr this could cause an error, as the command would only work with raw files with the standard naming convention (e.g. run0001.fits). All the functionality that the **Open...** command enabled is now available via the **Commands** menu. Therefore the **Open...** command is no longer available.

5.1.2 The Options Menu

This is unlikely to be needed in normal use.

The **Show Tasks...** item displays the status of the subtasks which the data reduction system uses to do its work.

The **Tcl Command...** item allows a Tcl command to be entered directly and exists mostly for debugging purposes.

5.1.3 The Commands Menu

The **Commands** menu contains the following items:

Reduce... --- This command opens a file and reduces it. In most cases this operation would be more easily done using the **Reduce** button on the **Data** page, or the automatic reduction method. This menu item is occasionally useful to reduce a file which is not part of the standard set loaded with the Setup button.

Combined Reduced Runs... --- This command is used to combine a number of reduced files on the same field to produce a combined frame of improved signal-to-noise. The frames are combined using a sigma clipping algorithm after adjusting the continuum levels, on a fibre-by-fibre basis to match the median level. This algorithm gives better signal-to-noise than the median used previously. See Section 3.9.

Find Fibres... --- This command is used to generate a new fibre position file from a fibre flat field exposure. This is only relevant for 2dF data. See Section 3.3.

Spectrograph Focus... --- This command is used to reduce a pair of Hartmann shutter exposures to provide information on the spectrograph focus. A flat field should be reduced first to provide a tram-line map, and then the spectrograph focus command can be used to reduce a pair of arc exposures taken with Hartmann shutters A and then B closed. The output is a measure of the arc line shifts binned into an 8x8 grid over the CCD. This is normally done by the Support Astronomer or technical staff.

Get Class... --- This command displays the class of a data file (see Section 6.3).

Set Class... --- This command is used to set the class of a data file. See Section 6.3.

Plot... --- This command plots a file in one of the plot windows. It is equivalent to the **Plot** button in the **Data** page, but allows any file to be plotted, not just those that have been loaded into the system.

Hardcopy Plot... --- This command outputs a hardcopy plot as a postscript file. It is equivalent to the hardcopy option with the **Plot** button in the **Data** page, but allows any file to be plotted. The type of plot produced is controlled by the parameters setup in the **Hard** tabbed page.

Plot Tram Map... --- This command is used to plot a tram line map overlaid on the image from which it was generated.

Show Header Info... --- This command displays the information in the FITS header of a file. It is equivalent to the **Show Header** button in the **Data** page, but allows access to the header of any file.

Show History Info... --- This command displays the information in the history extension of a file. It is equivalent to the **Show History** button in the **Data** page, but allows access to the header of any file.

Show Fibre Info... --- This command displays the information in the fibre header of a file. It is equivalent to the **Show Fibres** button in the **Data** page, but allows access to the header of any file.

5.1.4 The Help Menu

This menu controls the enabling and disabling of balloon help information which is provided by default for most aspects of the user interface.

5.2 The Automatic Reduction Section

This section is used to control automatic data reduction. In 2dfdr, automatic reduction is taken to mean reduction of a sequence of files in a single run, as opposed to reducing files individually.

5.2.1 The Setup Button

The **Setup** button is used to load files into the list on which automatic reduction will be performed. As discussed in Section 3.1 these files must obey a naming convention. Once

loaded, the files are accessible through the **Data** page. The number of files loaded and the number which have been already reduced are indicated on the display.

5.2.2 The Start Button

The Start button starts automatic reduction. This will cause all files in the automatic reduction list that are not already reduced, to be reduced. The sequence of reduction is chosen according to the priority of the various data file classes to ensure that calibration files are reduced before the data that need calibrating.

5.2.3 The Stop Button

The Stop button stops automatic reduction after reduction of the current file has completed. Use the stop button, followed by the abort button in the execution task window to abort the reduction currently in progress.

5.3 The Data Page

The “Data” page is selected by means of the **Data** tabbed page on the left of the screen. It can be used to select any file that is known to the system. Known files are all those loaded into the automatic reduction list by means of the **Setup** button.

Files can be selected by run number. Either step through the run numbers using the up and down arrow keys, or type a run number into the entry field. Alternatively, files can be selected by file name using the **File:** section.

The class, status (whether the file is reduced or not), and the name of the reduced file (if any) are displayed for the selected file.

Buttons in the **Data** page provide the following operations on the selected file.

Plot --- Plots either the raw or reduced file on the screen or as hardcopy.

Show Header --- This displays the FITS header of the file.

Show History --- This displays information from the “History” structure of the reduced file. This shows when the file was reduced, what calibration steps were used and which calibration files were used.

Show Fibres --- This displays a list of fibre information from the header, including the object names, RA, Dec, magnitude etc.

Reduce --- This reduces the selected file. If the file is already reduced the button changes to **Re-Reduce**.

Unreduce --- Removes this file from the list of reduced files, so that it will be reduced during a subsequent automatic reduction.

5.4 The Parameter Pages

The other tabbed pages in this side of the window are used to set parameters which control data reduction or display.

5.4.1 General

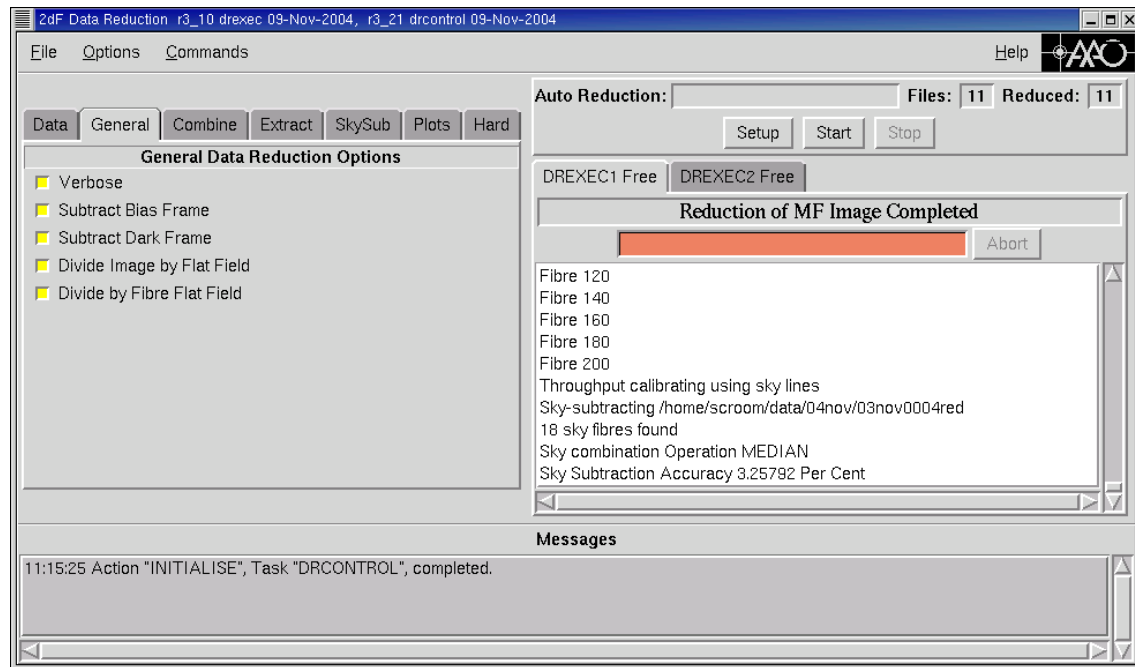


Figure 5 The main 2dfdr GUI showing the general parameters page.

This contains a number of check buttons which can be used to turn off some stages of the data reduction (see Figure 5).

The **Verbose** option, if turned off, causes the number of messages output during reduction to be much reduced.

Subtract Bias Frame, **Subtract Dark Frame**, and **Divide Image by Flat Field** are all on by default, though they won't happen if no suitable calibration file is available.

The **Divide by Fibre Flat Field** option is turned on by default. This divides extracted data by a fibre flat field if one is available.

5.4.2 Combine

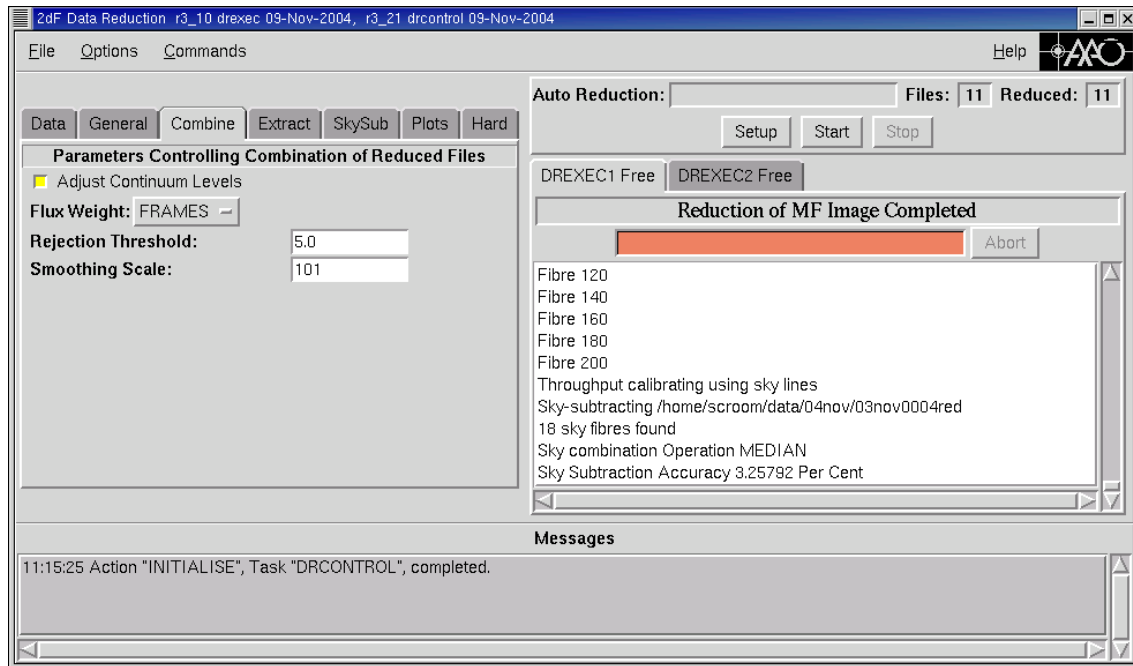


Figure 6 The main 2dfr GUI showing the combine parameters page.

This section controls the method used when multiple reduced frames are combined (see Figure 6). It applies to the combination of reduced runs using the **Combine Reduced Runs...** menu command, or to the automatic combination of offset sky frames, which occurs during normal reduction. See Section 3.9 for more information.

Setting the **Adjust Continuum Level** option causes the continuum level to be adjusted for each fibre by subtracting the difference between a smoothed continuum and the median for the data being combined. This is on by default when combining object frames to allow for variations due to seeing, telescope tracking etc., but can optionally be turned off. The setting is ignored when combining offset sky frames, to ensure that accidental alignments with stars get rejected in the combination. See Section 3.9.1.

Setting the **Flux Weight** option can be set to NONE, FRAMES or OBJECTS and can cause the spectra to be combined using optimal flux weighting. This is useful if data are taken in varying seeing or cloud conditions, or if frames have different exposure times. Flux weighting is off by default. See Section 3.9.2.

The **Rejection Threshold** is the number of sigma deviation from the median of the combined frames at which a point is rejected as a cosmic ray (default is 5).

The **Smoothing Scale** is the length of the median smoothing applied to get the smoothed continuum during the continuum adjustment phase (default is 101).

5.4.3 Extract

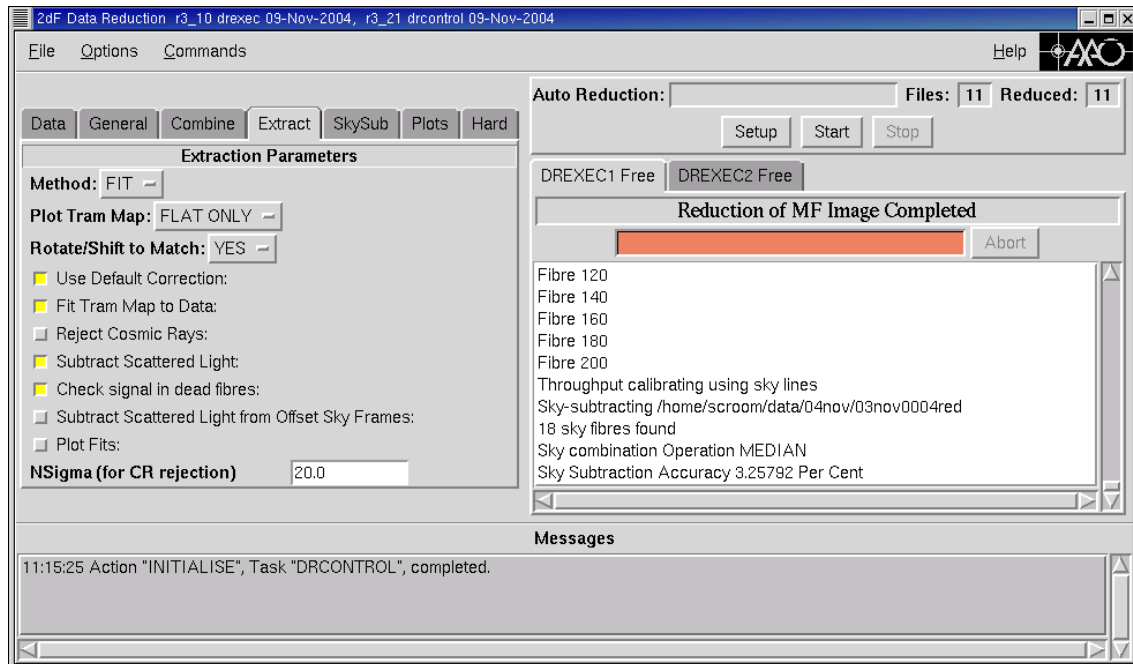


Figure 7 The main 2dfdr GUI showing the extract parameters page.

This section contains parameters controlling the fibre extraction and tram-line map generation process (see Figure 7). See Section 3.4 for more info.

The **Method** menu selects the fibre extraction method. The `TRAM` method performs a simple sum of the pixels is the default method. The `FIT` method performs optimal extraction and handles fibre overlap by simultaneously fitting profiles to overlapping fibres. See Section 3.4

The **Plot Tram Map** option causes the tram-line map to be plotted overlaid on the data, during the reduction process. There are three options: `YES`, `NO`, and `FLAT ONLY`. If selected, the plot is put up twice, both before and after a shift and rotation correction is applied to match the data. If the `FLAT ONLY` option is chosen, the plotting only occurs for flat fields. See Section 3.3.1.

The **Rotate/Shift to Match** option causes the tram-line map to be adjusted by means of a rotation and shift to match the data. There are three options: `YES`, `NO`, and `FLAT ONLY`. If the `FLAT ONLY` option is chosen, the operation only occurs for flat fields. It normally needs to be set to `yes` for 2dF since flexure in the spectrograph means that at least a shift correction is needed for each data frame. The matching operation can fail in a frame with very few fibres illuminated. In this case the **Rotate/Shift to Match** option can be turned off, but it will be necessary to use a tram-line map derived from a frame taken at the telescope position to avoid problems with flexure.

Use Default Correction causes the software to add a correction to the tram-line map derived from the ray tracing model of the spectrograph, based on the empirically derived difference between the model and typical actual data. This option should normally be on. The only reason for turning it off is when a new correction map is being derived.

Fit Tram Map to Data controls the final step of the derivation of a new tram-line map, in which a surface fit to the difference between the data and the tram-line map is applied as a

final correction. Normally this option should be on, but sometimes low signal or noise in some part of the frame may mean that a poor fit is obtained in some regions. In this case better results may be obtained by turning this option off.

Reject Cosmic Rays controls whether cosmic rays are rejected during the extraction process. Cosmic ray rejection with the default threshold should work in most cases, but with very high signal-to-noise data it may result in rejection of real features. In this case it may be better to turn it off.

Subtract Scattered Light controls subtraction of background light from the data before extraction using a fit to the “dead” fibre light levels. However, scattered light subtraction is not performed for sky frames (class MFSKY) unless the **Subtract Scattered Light from Offset Sky Frames** option is also selected. Also, scattered light subtraction requires at least 2 dead fibres to work properly, but better results will be obtained if more dead fibres are available; if there are insufficient broken fibres, 2dfdr will fail.

Check Signal in Dead Fibres This causes the software to check the signal level in each dead fibre (when reducing the initial flat field), and remove it from the dead fibres list if it appears to be not truly dead. The resulting list is written out as a deadfibres.dat file, and will get used for all subsequent reductions.

Subtract Scattered Light from Offset Sky Frames turns on scattered light subtraction from sky frames as well as other frames. This is separately controllable, since offset sky frames usually have very low scattered light levels and low signal levels, and there is a possibility that the scattered light subtraction process could introduce excess noise.

Plot Fits turns on plotting of the selected fits to the data during the scattered light subtraction and fit extraction.

NSigma (for CR rejection) controls the number of sigma which a point has to deviate from the profile to be rejected as a cosmic ray. The default value of 20 is about the lowest value that is found to be reasonably safe, i.e. unlikely to reject anything which is real in typical data.

5.4.4 SkySub

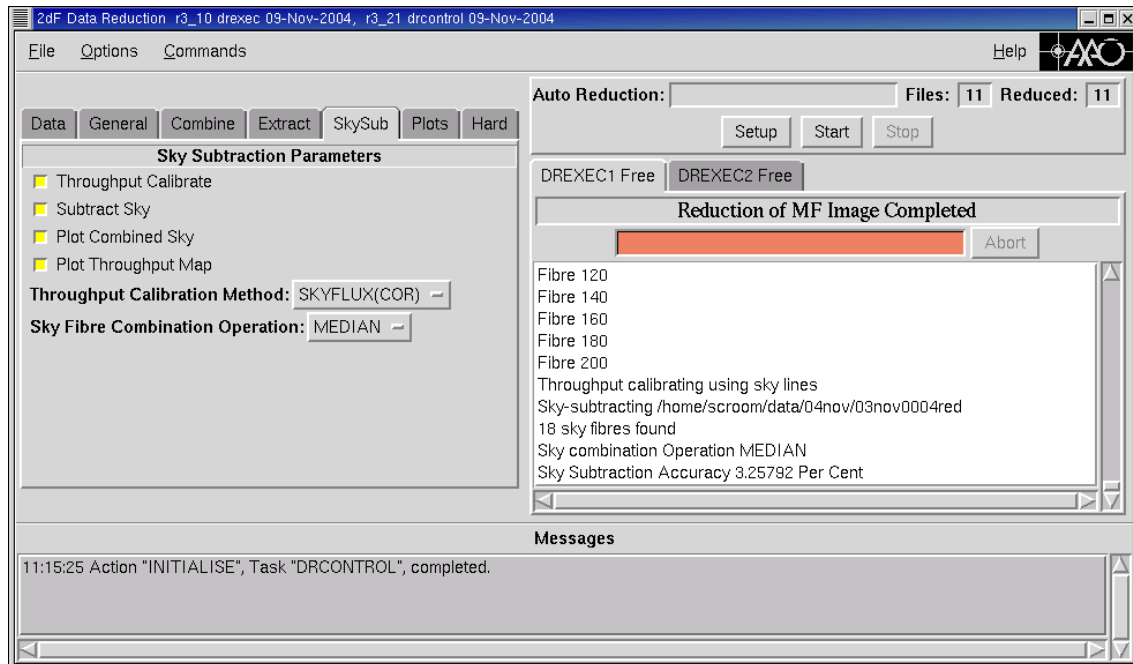


Figure 8 The main 2dfr GUI showing the sky subtraction parameters page.

These parameters control sky subtraction. Either throughput calibration (see below) or sky subtraction may be turned off. See Figure 8.

The **Throughput Calibration** option calibrates the data throughput using either a twilight/offset sky observation or the skylines/skyflux methods.

The **Subtract Sky** option causes the sky to be subtracted from the data using the sky fibres specified in header or in a skyfibres.dat file.

The **Plot Combined Sky** option causes the sky spectrum from the combined sky fibres to be plotted during each reduction. The **Plot Throughput Map** similarly causes the throughput map to be plotted during each reduction. NOTE: it is not really possible to see both plots, since one is displayed immediately after the other. To see plots, **Plot Fits** in the **Extract** menu must be turned on.

The **Plot Throughput Map** option causes the throughput map to be plotted during each reduction.

The **Throughput Calibration Method** provides multiple options for calibrating the fibre-to-fibre throughput. The OFFSKY option is the default and determines the throughput based on the signal in the combined offset sky frames for the fibre configuration. The SKYLINE and SKYFLUX methods are alternatives which can be used if no offset sky frames are available (and are in practice, the methods usually used). These determine the throughput from the strength of sky lines in the actual data frame being calibrated. They work as well as the OFFSKY method when there are sufficient sky lines, e.g. at low dispersion and/or in the red part of the spectrum. The SKYFLUX methods are generally preferred to the SKYLINE methods as they are robust against variations in the spectral PSF across the detector.

The **Sky Fibre Combination Operation** menu sets the operation used to combine the sky fibres in the data before subtracting (**MEDIAN** or **MEAN**; **MEDIAN** is the default). See Section 3.7.

5.4.5 Plots

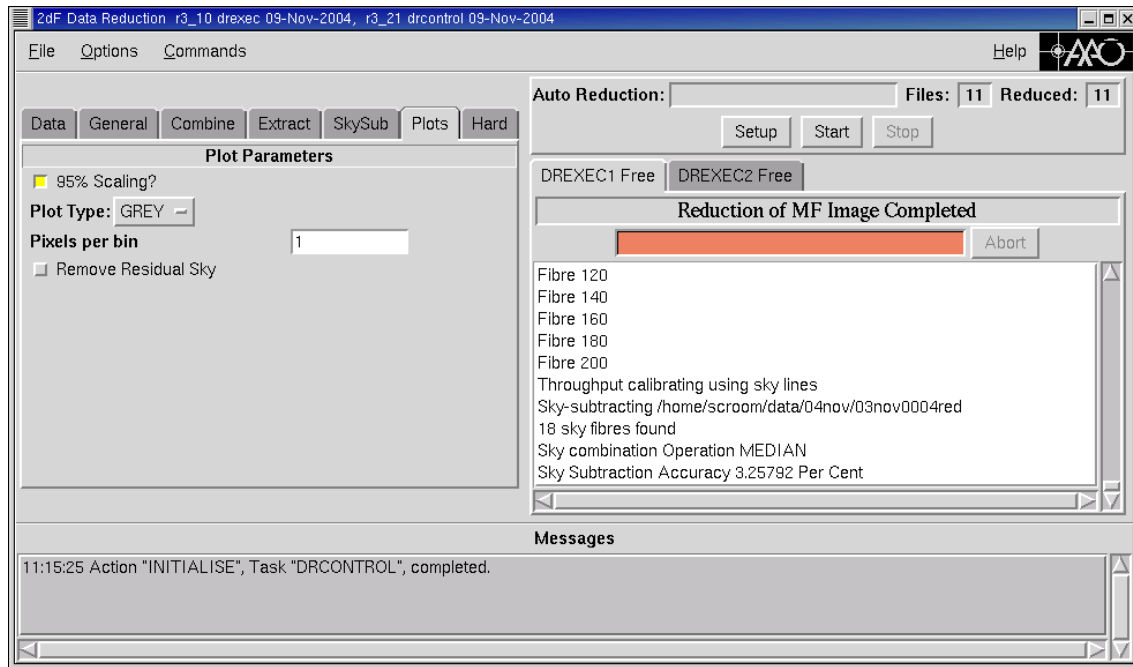


Figure 9 The main 2dfdr GUI showing the plotting parameters page.

These parameters control plots on the screen as a result of the **Plot** button or the **Plot...** menu entry (see Figure 9).

The **95% Scaling?** option scales plots between a high and a low scaling level which exclude the top and bottom 2.5% of the data values. This is the default option, if it is turned off data is scaled between the minimum and maximum values.

The **Plot Type** options controls how image data is displayed. The options are **COLOUR** for a false colour plot, **GREY** for a greyscale plot, **CONTOUR** for a contour plot, and **CVMAG** for a plot of observed counts in the spectra vs. the expected magnitude. This last option also estimates a relative zero-point of the data frame.

Pixels per bin controls the binning of data displayed as spectra.

The **Remove Residual Sky** option causes the strongest sky line at 5577 angstrom to be removed from plots by interpolating across it.

5.4.6 Hard

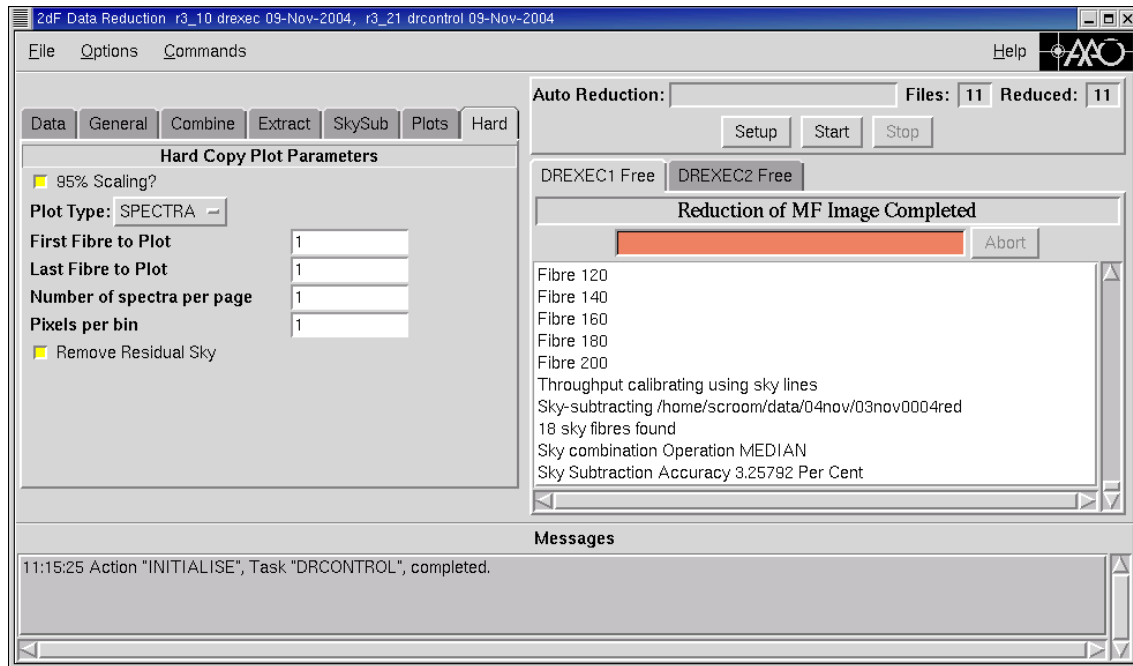


Figure 10 The 2dfdr main GUI showing the hardcopy plotting parameters page.

These parameters control hardcopy plots (see Figure 10). Some of them are the same as parameters in the **Plots** section. The additional option is to plot data as multiple spectra with a number of spectra per page. For example to plot all 200 fibre spectra, 20 to a page, set the parameters as follows:

Plot Type --- SPECTRA
First Fibre to Plot --- 1
Last Fibre to Plot --- 200
Number of spectra per page --- 20

Only certain numbers are supported for the number of spectra for page. Other values will be rounded to the nearest supported value. 20 is the maximum.

5.5 The Execution Task Section

This section is also organized as a widget, with two pages for the two execution tasks, DREXEC1 and DREXEC2. Every operation which involves accessing the data files is dispatched to one of these tasks for execution (except plotting operations which go to special plot tasks). Having two tasks means that more than one operation can be carried out at the same time. In principle it is possible to reduce two files at the same time, though this is not recommended as there may be conflicts with simultaneous access to the same files. However, the two tasks make it possible to do simple operations such as setting the class of a file, or viewing a FITS header while reduction of another file is proceeding. If necessary more execution tasks will be loaded as they are needed.

Each execution task contains a message region in which messages from the task are displayed. There is also a progress bar in which the progress of data reduction is indicated and a description of the current step in the data reduction process is shown.

The **Abort** button is used to abort reduction of the current file. It may not take effect immediately as the status of the button is only checked at intervals during the reduction process.

5.6 The Plot Windows

On start-up the system creates two plot windows, one labelled “General Plots” and one labelled “Diagnostic Plots”. The diagnostic plots window is used for graphical output generated during the data reduction process, e.g. plotting of tram maps, fit extractions, combined sky spectrum, or throughput maps. The “General Plots” window is used for graphical output resulting from the **Plot** button or the **Plot...** menu entry.

5.6.1 Interacting with Plots

Some features of the plots can be controlled using the buttons to the left of the plot window. Other options are obtainable by placing the cursor over the plot and typing keys on the keyboard. The main options available in this way are as follows:

X	Plot a cut through the image in X direction.
Y	Plot a cut through the image in Y direction.
Z	Zoom in by a factor of 2.
O	Zoom out by a factor of 2.
P	Centre plot on cursor indicated position.
[]	Select a region which will be expanded to fill the display.
H	Set the high scaling level to the value of the point under the cursor.
L	Set the low scaling level to the value of the point under the cursor.

In addition, clicking the mouse button on a point causes the position and value of the point to be output in the message window at the bottom of the plot window. For a full list of interactive plotting options press “?” with the cursor within the plotting window.

5.6.2 Plotting Fibre Spectra

If the file being displayed is a reduced multi-fibre image, then an X cut through the data (obtained with the **X** key) will be a plot of the fibre spectrum through the cursor position. It is then possible to step through the fibres using the **Next** and **Prev** buttons.

5.6.3 Changing the Size of the Plot Window

The size of the plot window can be changed to a number of different settings using the **Size** menu. A change in size will lose the current plot. The file has to be replotted in the new size plot window.

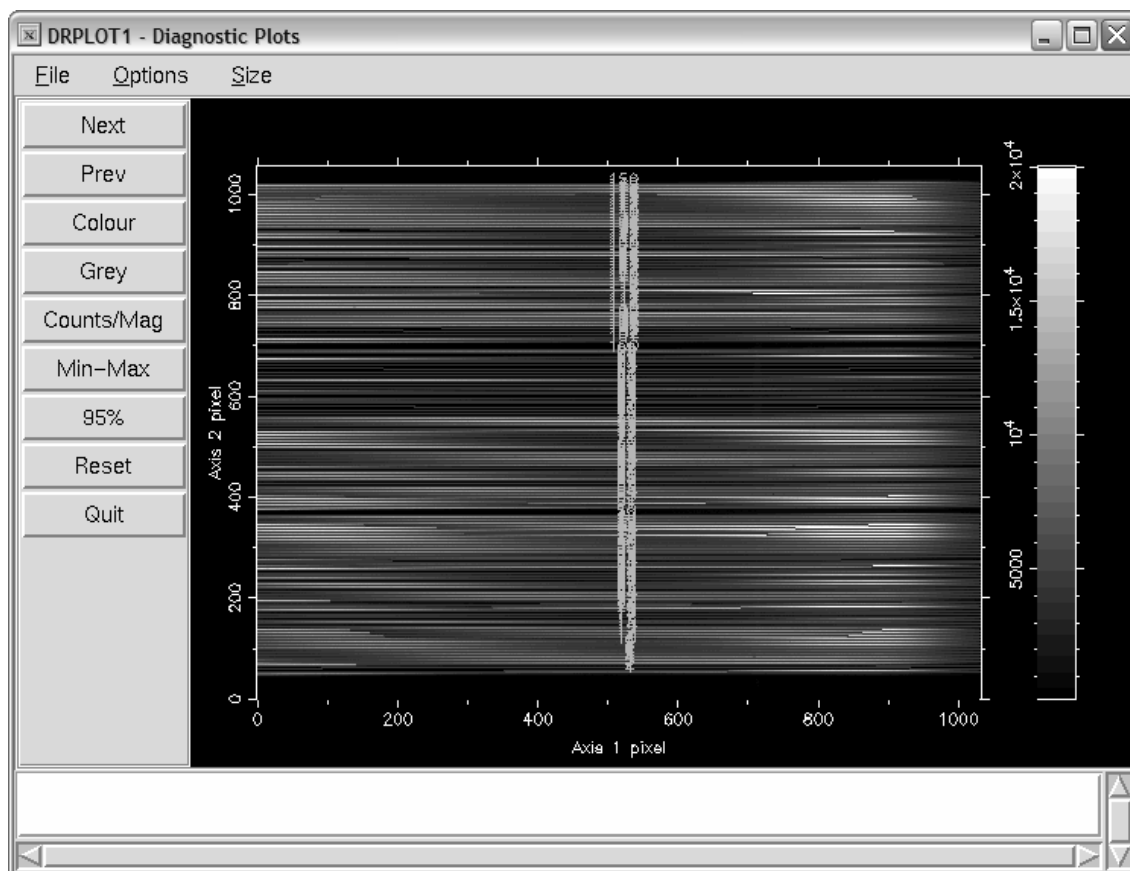


Figure 11: The Plot Window

5.6.4 Multiple Plots

By default when a new file is plotted it will overwrite the one already in the plot window. To prevent a plot being overwritten click on the Lock check box at the lower left of the window. If a plot window is locked and a new file is plotted, then a new plot window will be created to receive it. There can be up to three “General Plot” windows at any one time.

5.6.5 Making Hard Copies of the Screen Plot

The **Print...** command in the **File** menu of the plot window can be used to output the current screen display as a postscript file or send it directly to a printer. Note that the result will be output at the resolution it is displayed on the screen. Better quality hard copy will be obtained from a larger plot window. Alternatively, hardcopy output can be produced directly from a file using the **Hardcopy Plot...** command in the **Commands** menu of the main window.

6 Old 2dF Data

6.1 Fits Header Items

Data taken before October 1997 will not contain all the header information needed for reduction. The necessary header items must be added as described below. If your data was taken from October 1997 onwards you should be able to ignore this section.

To be usable by the reduction system the following header items must be present.

Keyword	Usage
LAMBDAC	Central Wavelength (Angstroms)
GRATID	Grating ID (e.g. 300B, 1200V etc.)
GRATLPMM	Grating lines per mm
ORDER	Grating Order
SPECTID	Spectrograph ID (A or B)
SOURCE	Spectrograph Source (“Plate 1” or “Plate 0”)
LAMPNAME	Calibration lamp used for arc exposures

The wavelength calibration lamp exposures need the name of the lamp in the FITS item LAMPNAME. This should be CuAr for the Copper/Argon lamp or Helium for the helium lamp. If spectrograph information is not in the headers the missing items can be added using the Figaro FITSET command. A shell script to add these items could be set up as follows:

```
#!/bin/csh
figaro
fitset $1 LAMBDAC 5880.0 'Central Wavelength'
fitset $1 GRATID 300B 'Grating ID'
fitset $1 GRATLPMM 300 'Grating Lines per mm'
fitset $1 ORDER 1 'Grating Order'
fitset $1 SPECTID A 'Spectrograph ID'
fitset $1 SOURCE 'Plate 1' 'Spectrograph Source'
```

Then for the arc exposures you will have to set the additional LAMPNAME item which can also be done with the fitset command.

The other thing required in the files is the NDF CLASS item which identifies to the data reduction system how to process the file. This is set up with the data reduction system itself.

6.2 Object and Sky Fibre information

For data taken from October 1997 onwards fibre information is included in the headers. The data reduction system will automatically know which fibres are sky fibres for example.

Data taken before October 1997 does not contain headers describing the information on each fibre. For post October 1997 data, it may also be the case that certain header items are wrong or missing (though this is unusual). For these runs, a utility program called `tdffix` is provided with the data reduction system to fix the headers of the 2dF data files.

The input needed to this program is the `.sds` configuration file used to set up the field, and the 2dF fibre database file “`spec fibres.txt`” (specifically the version used when the data were taken). “`spec fibres.txt`” is available from staff at Siding Spring.

Use the command:

```
tdffix infile outfile CONFIG=configuration.sds FIBRES=spec-fibres.txt
```

where “infile” is the 2dF data file that needs to be fixed, “output” is the corrected data file, and “configuration.sds” should be replaced by your actual configuration file.

Tdffix can also be used to fix other header items, in other words to set or override the values of FITS keywords used by 2dfdr. As an example:

```
tdffix infile outfile SPECTID=A ORDER=1
```

See the tdffix man page for more information about tdffix and how to use it (“man tdffix”).

6.3 Setting the Class of the Data Files

You can ignore this section if the correct run command setting (i.e. NORMAL, FLAT, SKY, ARC etc) in the 2df control task was used when you took your data. The 2dF data reduction system will use the RUNCMD item written into the header to determine the class of your files. If not, you must set the class as described below.

In order to reduce a data file the system has to know the data file type. It does this using an NDF CLASS extension stored within the file. To set this up you need to be running the data reduction system. Use the **Set Class** item in the **Commands** menu. This will bring up a file selection dialog to allow you to select a file, followed by another dialog to allow you to set the class. The class should be set as follows:

Class	Name Usage
BIAS	Dark (shutter closed) one second integration
BIASCG	Group of reduced BIAS frames
BIASGRP	Group of BIAS frames
DARK	Dark (shutter closed) of arbitrary length frame
DARKCG	Group of reduced DARK frames
DARKGRP	Group of DARK frames
LFLAT	Long slit (full chip) flat field frame
LFLATGRP	Group of LFLAT frames
MFARC	Multi-fibre arc (lamps having various known lines) frame
MFFFF	Multi-fibre flat field (quartz light for uniform spectrum) frame
MFFLX	Flux standard frame
MFOBJECT	Multi-fibre object data frame
MFSARC	Extracted MFARC frame
MFSFFF	Extracted MFFFF frame
MFSFLX	Extracted MFFLX frame

MFSKY	Offset sky or twilight sky (sky subtraction and/or throughput calibration)
MFSOBJECT	Extracted MFOBJECT frame
MFSPIRAL	Multi-fibre object data frame from SPIRAL instrument
MFSKY	Extracted MFSKY frame

6.4 Data Contamination by Artificial Lights

Some early data taken with the 2dF shows some contamination of the spectra by artificial lights on the 2dF electronics and power supplies. Usually this just affects a few fibres on each image. The contamination takes the form of emission spectra from neon lamps (see Figure 12) which show a series of emission lines mostly in the range from 6000 to 7000 Å as well as broad emission.

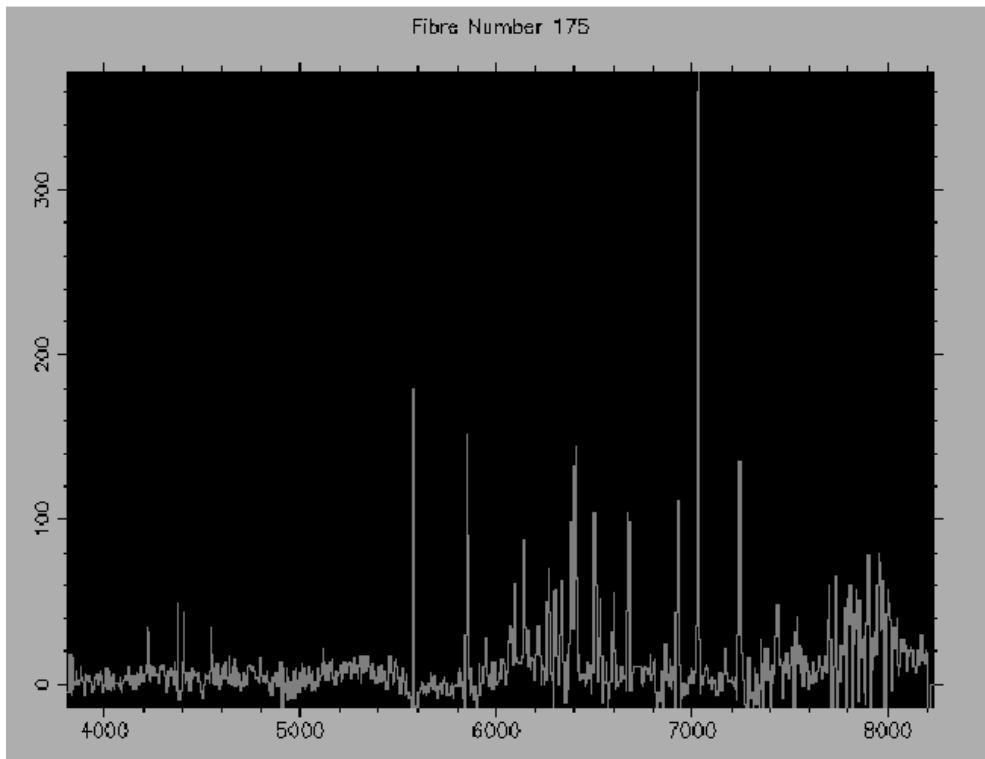


Figure 12: Fibre spectrum contaminated by neon emission from a neon lamp on the 2dF electronics.

7 Nod and Shuffle data reduction

Nod and Shuffle (N&S) is a mode of observing aimed at reducing the systematic errors in sky subtraction to an absolute minimum. For details of the method see Glazebrook & Hawthorn (2001, PASP, 113, p197) and articles in AAO newsletters no. 87 and 105. Briefly, this method involves nodding the telescope to sky, while shuffling the charge on the detector. This results in two sets of spectra on the detector one on target, and the second on sky. Optimal (near Poisson) sky subtraction is realised by simply subtracting these two sets of data. On 2dF the charge is shuffled into alternating retractor blocks of 10 fibres, meaning that

only half the fibres are available for use. A ring covering the fibres at the parked position on the field plate masks off the unused fibres. The typical shuffle is ~50 pixels.

2dfdr recognises N&S data by looking at the METHOD header keyword. If this is equal to "Shuffle" then the data is assumed to be N&S data. The key step in N&S data reductions is that a shift and subtract is carried out on the un-extracted data frame. This is done directly after the "rotate and shift to match" is done to align the tramlines (if the shift and subtract is done before this stage there is often not enough counts in the spectra to get a good tramline match). Apart from this the data is reduced much like any other set of 2dF data. The following is a brief recipe for N&S reduction:

- Run **Find Fibres...** on the masked flat field.
- Reduce the masked flat field as normal.
- Reduce the masked arc as normal.
- Reduce the object frames, turning off: scattered light subtraction, fit tram map to data and reject cosmic rays. Turning on: rotate/shift to match, and use default correction. TRAM extraction is recommended, as the FIT method struggles on very low S/N data (where the sky has already been removed).
- Combine the data as normal. The combine algorithm will check for both positive and negative cosmic rays in N&S data.

There is a .idx file that contains suitable defaults for N&S reduction: 2dfns.idx.

8 Using 2dfdr with other instruments

8.1 SPIRAL

SPIRAL is a 512-element IFU, originally with its own simple spectrograph. SPIRAL is not currently available on the AAT; it will be recommissioned for use with AAOmega, and this manual updated at that time. Any users with problems reducing existing SPIRAL data should contact the AAO.

8.2 6dfdr

6dF is the 150-fibre positioner and spectrograph on the UK Schmidt telescope. 2dfdr is able to reduce 6dF data, when run with the appropriate 6df.idx startup file. In this mode it is usually referred to as '6dfdr'.

8.2.1 Nomenclature

6dF data files are invariably given a prefix which refers to the field and grating rather than just the date, and placed in a directory indicating the date - e.g. /6dfdata/20041107/1234m567V0022.fits. This has both advantages and drawbacks over the date+run# file names used on 2dF- on the one hand, all data with a given prefix should be compatible; on the other hand, there is often confusion if the field is observed on more than one night. The CICADA data taking software limits the prefixes to 9 characters. Combined output filenames are up to the user, but the traditional format has always been e.g. 1234m567Vred.fits to mean the final combined object data with prefix 1234m567V.

8.2.2 Data orientation

Raw 6dF data has wavelength running from top (blue) to red (bottom), and fibre numbers running from 1 (left) to 150 (right). Reduced data has the same orientation as 2dF - left (blue) to right (red), and 1 (bottom) to 150 (top).

8.2.3 Automated tram-line fitting

The single main difference in 6dfdr is that the tram line mapping is fully automated as part of the MFFF reduction, using the known positions of the gaps in the fibre slit between fibres 50/51 and 100/151. If the Tram Map is plotted to the screen, it must be accepted, twice (first fitted to centres of spectra, then after rotate/shift), by hitting '**Quit**' (or typing 'q') on the DRPLOT1 window. Unlike 2dF, where the fit can be almost right, for 6dF it is always either perfect or rubbish.

Tram-line fitting failure is very rare. Causes to date have been (a) the data is so badly out of focus that two fibres are unresolved, (b) due to an unlucky arrangement of broken fibres (all three of 1/51/151 or 50/100/150), a unique fitting solution does not exist. In this case, the user must supply a file 'reallydeadfibres1.dat' or 'reallydeadfibres2.dat', in the data directory, containing a list of broken fibres for that field plate sufficient to guarantee a unique fit. There is an example in the \$DRCONTROL_DIR directory. 2dfdr then demands that no spectrum be found at these fibre positions when looking for the tramline fit. So make sure any fibres listed in the file are really broken, not just low transmitters, since otherwise the success of the reduction will depend on e.g. grating used or MFFF exposure time. Also note that the presence of this extra file will prevent any fit at all being found if the listed fibres are not (or are no longer) broken.

8.2.4 Scattered light subtraction

6dfdr also uses the fixed positions of the gaps in the fibre slit to measure the scattered light levels. These positions are supplied using the files 'deadfibres1.dat', 'deadfibres2.dat' either in the \$DRCONTROL_DIR directory or the data directory. So removing these files from \$DRCONTROL_DIR will in general prevent you from doing scattered light subtraction with 6dfdr.

You will get an error message 'DREXEC2:ArgCvt cannot convert "FALSE" to Integer ' when reducing the flat field with scattered light subtraction on but it is cosmetic only.

8.2.5 Initial dispersion solution

Like 2dfdr, 6dfdr needs a reasonable first guess at the dispersion solution to correctly fit the arc lines in the MFARC spectrum. However, unlike 2dfdr, this information is taken from lookup files in \$DRCONTROL_DIR for each grating. For very early data, these depend on the grating angle and the grating slot used (A-G). For subsequent data - which uses only a limited number of setups - the central wavelength and dispersion are hardwired into a file e.g. I316R.dat to mean the standard setup with grating 316R. Users with non-standard setups will need to make their own grating file in \$DRCONTROL_DIR, usually e.g. H316R.dat, with a reasonable guess at the wavelength solution in the same format as the files already there. The prefix letter must match the GRATSLOT keyword. The fit is in particular sensitive to getting the right dispersion; this can best be found iteratively by looking at the residuals of the arc line matches written to the Unix/Linux window.

8.2.6 Arc line lists

6dF has 4 arc lamps (He, Ne, HgCd, Rb) which can be used in any combination. This leads to a multiplicity of possible line lists demanded by the LAMPNAME keyword; the lists in \$DRCONTROL_DIR attempt to cover all sensible combinations.

8.2.7 6dF header issues

A bug in the Cicada software means that the gain (RO_GAIN) and read noise (RO_NOISE) are set to zero in the fits headers. 2dfdr then assumes that the gain and noise are $0.64e^-/ADU$ and $2.75e^-$, as appropriate for MEDIUM readout speed. For other readout speeds, RO_GAIN and RO_NOISE must be set to the correct values using 'sethead'.

In general, because of the much greater level of operator interaction with the Cicada CCD software (the UKST has no computer control of the telescope), the scope for operator error in the headers is much greater than with 2dF. Particular items that often give trouble are:

LAMPNAME (the arc lamp used) OBJECT (the .sds filename), and SOURCE (the field plate, 1 or 2).

8.2.8 6dF VPH ghosts

It is an unfortunate feature of any transmission grating used in Littrow (symmetric) configuration, that there is a ghost image of the slit unit, in the middle of the spectrum. The cause is a partial reflection back from the CCD, recombined by the grating in first order reflective mode, and re-imaged onto the detector. For 6dF, the ghost image is out-of-focus, covering 20-50 spectral pixels; it can be readily seen in the flat-field frames displayed at very high contrast. The total light in the ghost is ~0.01% of all light on the detector. The ghost can be moved spectrally by tilting the grating away from Littrow, at some cost in efficiency.

After observation, there is no cure, though scattered light and sky subtraction will tend to suppress it.

All 6dF VPH data suffers from this problem, though the effect is mostly cosmetic. AAOmega will suffer from this ghost for some gratings; but most have been made with slanted fringes (like a Venetian blind) to avoid the problem.

9 Intended future upgrades for AAOmega

2dfdr will provide much better reductions for AAOmega than for 2dF, because of the stability of the spectrograph, the uniform and well-sampled PSF, the completely resolved spectra, and the availability of a calibration long-slit. In addition, there are various 2dfdr upgrades still intended as part of the AAOmega project, to provide better or easier reductions.

9.1 Automated tram line mapping

For 6dF, the tram line mapping is fully automated, using the known positions of the gaps in the fibre slit. AAOmega will implement a suitably modified version of the same approach for both MOS and IFU modes, so the 'find fibres' command will become obsolete.

9.2 Automated data combining

It is intended that when doing an automatic reduction, all MFOBJECT frames of a given prefix (and with compatible grating, grating angle, field name etc) be combined automatically at the end of the reduction of all individual frames, according to the parameters set in the 'combine' menu.

9.3 Batch reduction

It will be possible to run 2dfdr on a given dataset from the command line. Combined with the automated data combining set out above, this means that fully reduced data can be returned from a single command line command.

9.4 Better scattered light subtraction

Precision equivalent widths and sky subtraction both depend on accurate characterisation and subtraction of the scattered light. The current model does a reasonable job in the case of sky limited observations, but was never designed for other situations. It is intended that the scattered light be self-consistently cleaned from the data - in the sense that the cleaned data convolved with the expected scattered light profile matches the observed data. In principal, this should give dramatic improvement in the scattered light subtraction, particularly when the objects cover a wide range of magnitudes.

9.5 Flux calibration

2dfdr currently does no flux calibration at all. Flux calibration involves (a) reducing a spectrophotometric standard star in the same way as the data using 2dfdr, (b) determining the transfer function by dividing this by the true spectrum, and (c) dividing the observed spectra by the transfer function. Steps (b) and (c) involve using IRAF or FIGARO. It is intended that these steps be included within 2dfdr, involving a new class of observation for spectrophotometric standards.

9.6 Mini-shuffling

Mini-shuffling involves nodding the telescope to adjacent sky, while shuffling the data on the CCD by just a few pixels. If the as-built performance of AAOmega matches expectations, it should be possible to extract the marginally resolved ON-OFF pairs of spectra, with each ON-OFF pair then fully resolved from the next pair. The advantage is that unlike normal N&S data, all fibres can be used. However, the utility of mini-shuffling depends not only on the optics, but also on the sky-subtraction precision achieved with dedicated sky fibres - the latter being always a much more efficient use of the telescope if the sky subtraction meets requirements.

10 Trouble-shooting

When 2dfdr works, it's like magic. When it doesn't, the multiple quick-fire error messages are often extremely opaque. Work your way all the way back to the first to try to find the root cause of the problem, and check the Unix/Linux window also.

After a crash, you will generally be left with the interface still visible, and one of the two drexec processes still alive. However, it is very rare to be able to fix the problem without exiting and restarting 2dfdr. The suggested procedure is, having decided upon a possible solution, to exit 2dfdr, do a 'cleanup', delete any files of the form `_*.sdf`, `t????.sdf`, delete any partial reduction files for the frame where the failure occurred (of the form `ex.sdf`, `im.sdf`, `red.sdf` and `tlm.sdf`) restart 2dfdr, and start from the frame where the problem occurred.

10.1 2dfdr Plotting fails

In some cases you may get an error when trying to plot data within 2dfdr, or when 2dfdr tries to plot something during a reduction. Typically this results in an error message of the form:

'GROPWK - xwindows is not a valid workstation name', where xwindows may be replaced with something like x2windows. This error is caused by a bug in a STARLINK library, which means that the DRCONTROL_DIR environmental variable must be less than 40 characters. The only solution is to move your installation of 2dfdr to a location with a shorter path.

10.2 The Open... command fails

This is not a problem in the latest version of 2dfdr as the **Open...** command has been superseded. However in some previous versions 2dfdr only allowed you to open files using the **Open...** command if they are in the standard format, e.g. run0001.fits, 10sep0002.fits etc. Other file names (including reduced files with names e.g. run0001ex.fits) will cause an error. All the functionality available when a file is opened is still accessible using the list of functions in the **Commands** menu.

10.3 Header problems

Very often, the problem is a missing file in \$DRCONTROL_DIR, and very often (at least for 6dfdr), this is caused by an error in the fits headers. For older .sdf data files, these can be examined and corrected by the Figaro 'fitskeys' and 'fitset' commands; for fits files, the commands `gethead` and `sethead` have been provided.

10.4 gethead and sethead

Command line commands `sethead` and `gethead` have been included in the 2dfdr release. They are not AAO software, they are part of the WCSTools software package (<http://tdc-www.harvard.edu/software/wcstools/>). They extract, change or insert header items for fits files, and are invaluable for sorting out botched headers. The usage is

```
gethead file.fits KEYWORD
sethead file.fits KEYWORD=value
```

10.5 Tramline problems

Very often, 2dF reduction problems are caused by tramline fitting errors. But this is not always obvious. In particular, incorrect tram line fitting will often lead to a (missing) spectrum from a broken fibre being reduced as if it were there, with a crash at either the flat-fielding or the arc-fitting or the sky subtraction stages. If the reduction falls over for a particular named fibre, suspect this first.

Tramline problems can be caused by a number of problems. The most common are:

1. In 2dF data, the **Find Fibres...** function has not been run, or the fibres have been mis-identified in the process of running **Find Fibres...** **Solution:** run/re-run **Find Fibres...**
2. In 6dF, the problem is much rarer. It can be caused by badly out-of-focus data, or so many broken fibres that there is no unique solution. When the automated fitting fails, an interactive display is triggered, and fibres can be laboriously added or deleted with 'a' and 'd', starting from the bottom. If the problem is caused by broken fibres, judicious use of the `reallydeadfibres1/2.dat` file as set out above will allow an automated solution.

10.6 Skyflux throughput calibration method fails

In some cases 2dfdr may fail stating that there was an error in the throughput calibration, e.g. with a message: `DREXEC1:! Error in fibre-throughput calibration`. The **Skyflux(corr)** and **Skyflux(med)** algorithms are designed to fail if they determine a bad throughput value for either a program (P) or sky (S) fibre. This can happen for a variety of reasons, often not at all related to the actual throughput calibration process. One is that there are cosmic rays near several of the sky lines and the cosmic ray rejection during extraction is turned on. This results in pixels that are flagged as bad within the windows used to sum the sky line flux, which means that the sum is also defined as bad. This is usually only a problem if there are a small number of sky lines (1 or 2) that are being used for the throughput calibration. The solution is to turn off the cosmic ray rejection (it can still be applied when combining the extracted data). The error message will list the fibres that are found to have bad throughputs (see also the messages on the terminal window). If many fibres are found to have bad throughputs this suggests that there is either a problem with the wavelength calibration [so that the sky lines aren't where they are expected - check that the correct arc is being used and that the correct FITS keywords (e.g. LAMPNAME) are in the ARC frame], or the mapping of objects to fibres is wrong (so that unused fibres are listed as program or sky fibres). If only a few fibres have bad throughputs this is most likely because there are fibres allocated to objects which actually fall off the edge of the CCD (usually the first or last fibres). The solution for this is to edit the fibres extension for these objects by hand to set the type to N or U. Finally, it is possible that in some cases the algorithm simply fails due to a very bright object, with a particularly variable spectrum (e.g. a bright late M dwarf). In this case one of the other throughput calibration algorithms can be used.

10.7 Garbage reductions

2dfdr is designed to complete reductions without falling over, even when these reductions may not be useful. So always examine your output data. Sky residuals may have p-Cygni profiles, but should have zero flux on average; the position of well-know sky lines and/or absorption bands should be checked.

10.8 Poor sky subtraction

For example, if an arc frame is not available, 2dfdr will assign a default wavelength solution to the data and carry on regardless. In general, poor sky subtraction is often a sign of a poor dispersion solution for whatever reason.

2004 6dF data often suffered from a slippage of the slit vane during the series of frames forming a data set; extreme cases reveal themselves via poor sky subtraction as well as misplaced skyline wavelengths.

10.9 Unexpectedly low S/N

Tramline fitting errors in 2dF can lead to low S/N, because object fibres are misidentified as sky.

A very common problem with 6dF is that the data file extension listing the target names and positions is actually for another field. This can occur either because of a robot error and manual intervention, or because the wrong field plate was entered into the data by the observer. The signature - apart from all the target id's being wrong when individual spectra are plotted or when 'fibres' button is pressed - is very low signal-to-noise in data that looks ok on the 2D data frames. The low S/N is because random fibres, most of them object fibres, are

being used as sky fibres! If you have at least one file with the correct extension, there is a command line command 'extend_change.solaris' which will splice extensions from one file to another.

10.10 Artefact structures within high S/N spectra

In high S/N data, systematic spectrophotometric errors (caused by changes in the differential refraction during an exposure or by acquisition changes) may far outweigh the statistical error. So when data is combined, all data for each pixel, bar one, may be discarded as cosmic rays. The resulting spectrum has a characteristic 'choppy' appearance. To solve the problem, increase the tolerances on the 'combine' menu.

10.11 Cross-talk with bright neighbouring spectra

FIT extractions have much less crosstalk between adjacent spectra than TRAM extractions, and 6dF is much better than 2dF. But because the spatial profiles are not Gaussian, crosstalk still remains at a low (~1%) level. In general, if fluxes between adjacent objects vary by say an order of magnitude (either in overall brightness or because of a bright emission line), it is then easy to get spurious features within spectra. It is hard to see these in the reduced spectra, because the spectra have all been shifted as part of arc calibration. It is much easier in raw 2D data frames, or in the extracted (but not wavelength calibrated) `*ex.fits` files. Try reductions with and without scattered light subtraction, and with TRAM vs. FITS.