

SG/9.2

Starlink Project
Starlink Guide 9.2

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Introduction to Echelle Spectroscopy

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1 Introduction

Echelle spectrographs are available as common-user instruments at several observatories and satellites. These spectrographs offer the observer both a reasonably high **resolution** and a wide wavelength-coverage; at the expense of a fairly complex data-reduction procedure.

This document is intended as an introductory guide for observers new to échelle work. Experienced observers may wish to consult §5 for outline information on the main packages available for échelle data reduction.

1.1 Other Sources of Information

This Guide complements the Starlink *Echelle Data Reduction Cookbook* (Starlink document SC/3) which contains examples of data-reduction scripts, including templates for fully automated data reductions with ECHOMOP.

A significant part of the process of successful spectrum extraction is the preliminary handling of the **CCD** data frames. Those planning to use IRAF¹ should consult *A User's Guide to CCD Reductions with IRAF* (UGCRI) by Philip Massey. UGCRI is quite a good document for *any* user of CCD data, even those planning to use *e.g.* CCDPACK or FIGARO to do the preparation—the *CCD Reduction Cookbook* (SC/5) is the definitive introduction to this type of work.

IRAF users should look at the two documents for échelle data reduction within IRAF: *A User's Guide to Reducing Echelle Spectra With IRAF*, and *Guide to the Slit Spectra Reduction Task DOECSLIT*. These give a comprehensive description of the IRAF approach to échelle data. There is also a hypertext tutorial for DOECSLIT at

- <http://www.starlink.ac.uk/iraf/web/tutorials/doeslit/doeslit.html>

You may be able to access a local copy of this tutorial; consult your system manager.

There is an excellent guide tailored to the reduction of échelle data taken using the Hamilton Spectrograph: *Introduction to Echelle Data Reduction Using the Image Reduction Analysis Facility*, which is a Lick Observatory Technical report. (A PostScript copy is available from the Starlink Echelle Support Pages.) This is a complete step-by-step run through of échelle data reduction using IRAF—from CCD data to calibrated spectra.

The primary documentation for ECHOMOP is in *ECHOMOP—Echelle data reduction package* (Starlink document SUN/152). This document explains each of the data-reduction steps using ECHOMOP and includes some general advice and tips. There is also additional information and advice in the on-line HELP for ECHOMOP if you get stuck.

An up-to-date set of hypertext documents for Starlink échelle data reduction and related information; including hypertext help, bug reports, comments and news, is maintained at

- <http://www.star.ucl.ac.uk/~mjc/echelle/>

¹IRAF documents can be found in your IRAF installation; you do not need to get them from Tucson or a mirror. Check with your manager for details.

Terms in the body text of this Guide in **bold** are described in the glossary later in this document; if you cannot find the term you want there, you might try the *NASA Thesaurus*:

- <http://www.sti.nasa.gov/nasa-thesaurus.html>

2 An Echelle Spectrum

In ‘traditional’ spectrographs a dispersing element—typically a **diffraction grating** or **prism**—is used to produce the spectrum. This results in a single spectrum which can be imaged using a **CCD** or other type of camera. The data can then be extracted using a suitable program. The recordable part of the wavelength range covered by this type of spectrograph is limited by the size of available image sensors, *i.e.*, CCDs.

A quick inspection of a CCD image of such a spectrum will also reveal that much of the detector area away from the spectrum itself is unused. One method of optimising the use of the available detector area is to use an échelle spectrograph.

An échelle is a diffraction grating in which the rulings are much further apart than usual. This leads to spectra of very high **dispersion**, but only over a short wavelength range in each order. As well as being ‘short’, the high orders will overlap. To overcome this effect a **cross-dispersing** element is used to produce an **order separation**. Figure 1 shows a small part of such an échellogram recorded with a CCD camera. You can see a short part of three orders which run from the top to the bottom of the image at a slight angle. In the order to the right you can see a couple of absorption features. Several **cosmic-ray events** (bright spots) are also visible.

Echelle spectrographs for astronomy are designed so that the wavelength coverage in one order will overlap the coverage of the adjacent orders. (That is at least for the middle orders in the full échellogram—there may be some gaps at the extremes of the image.) Using a suitable detector—usually a CCD—these spectral orders can be recorded.

The extraction of an échelle spectrum from a set of images is, in principle, similar to the extraction of a single-order spectrum. Additional complexity arises because:

- There are more data to extract.
- The orders can have a more complex shape than those from a single-order instrument.
- The high **dispersion** used can make it difficult to distinguish between true spectral features and cosmic-ray events.
- **Flat fielding** the data can be difficult.
- In some cases adjacent orders overlap slightly in the spatial direction (there can be several reasons for this) making accurate background subtraction difficult.

Fortunately, there are several dedicated software packages available which address these specific features of échelle data reduction.

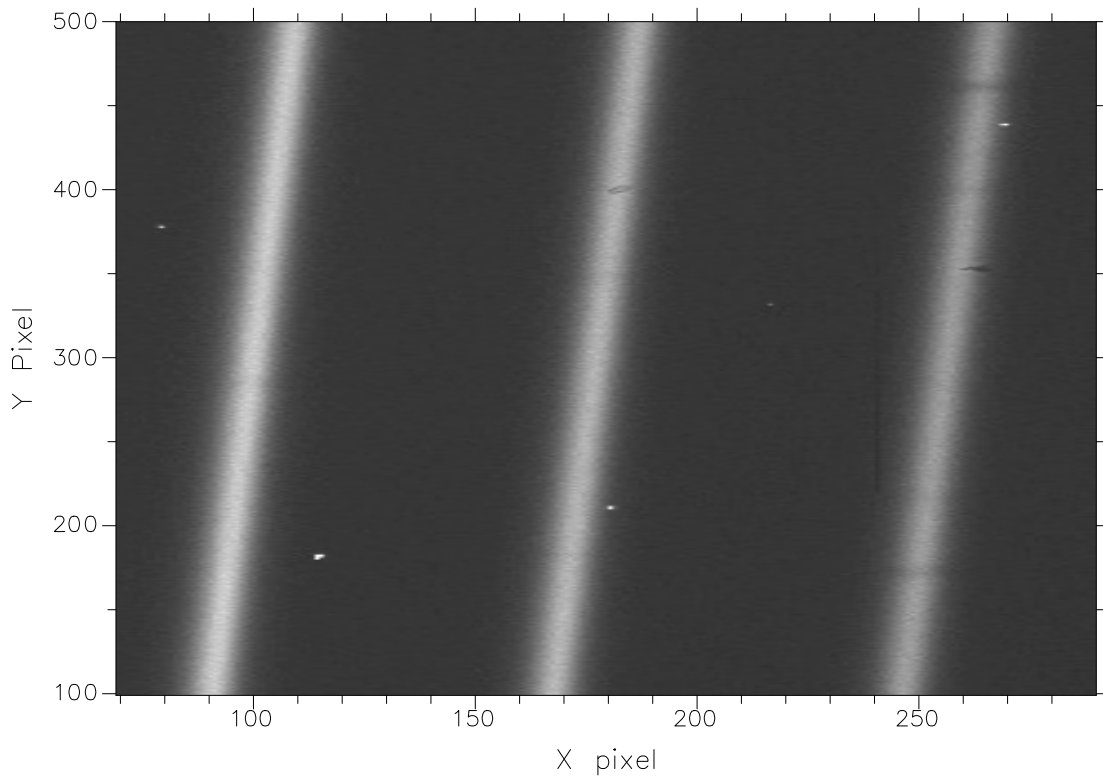


Figure 1: Echelle Image: Part of an échelle image produced with UCLES and a CCD camera.

3 Preparing for Observation

There is a comprehensive Starlink Guide for those preparing for an observing run—*Preparing to Observe* (Starlink document SG/10).

In this section some notes on what to be aware of prior to an observing run are given. In outline: to successfully extract and calibrate an échelle spectrum a complete set of reference frames should be obtained at the telescope.

You might want to refer to the more extensive discussion of CCD data calibration in: *A User's guide to CCD Reductions with IRAF*, the section entitled "How Many and What Calibration Frames Do You Need?"

3.1 What CCD Data Do You Need?

This is what you need to attempt 'textbook' échelle data preparation:

Bias frames Zero-second exposures taken with no signal light entering the instrument but with any pre-flash used for the object exposures present.

Dark frames Long exposures taken with the shutter closed. Typically, the exposure time used is similar to that selected for the object frames.

Flat-field frames Exposures taken with a suitable continuum lamp (usually Tungsten) as light source.

Arc frames Exposures taken with an **arc lamp** (usually Thorium-Argon) as light source, to be used for wavelength reference.

Object frames Exposures taken with a target object or reference object as the ‘light source’.

The arc and object frames will be processed by the échelle data reduction software. The bias and flat-field frames are used in the preparation of the CCD data.

3.2 Detector Pre-processing

A more complete introduction to the handling of **CCD** data can be found in the *CCD Reduction Cookbook* (SC/5), a brief outline is given here.

In order to remove detector-related effects a complete set of **bias**, **dark**, and **flat-field** frames should be obtained. It is important to *bracket* the science data exposures with complete sets of CCD characterisation frames. A post-observation review of these will reveal any image shifts. Having bracket frames allows the data to be accurately prepared even in the event that some time-dependent variation is found (as long as its a small, slow-varying effect).

See §4.1 for outline details of CCD data preparation.

In some cases it may be possible to not use any **bias frames**. Instead, a median value for the bias level is obtained by inspecting the **overscan region** in some or all of the object/arc frames. You can use fewer bias frames when you have a high signal-to-detector-noise ratio.

For exposure times limited by cosmic-ray event counts, the **dark current** in most CCD cameras is not a significant factor. The simplest way to decide whether to take dark frames is to take one of exposure time similar to that you are using for object frames, and check the signal level.

3.3 Flat Fields

Beware of flat fielding in échelle spectroscopy. For a stable spectrograph (*e.g.* **UCLES** which is in the **AAT** coudé room) you can take flat-field frames at any suitable time. For less-stable instruments it may be difficult to get a useable flat field. The problem is getting the object and flat-field orders to fall on the detector in the same place. In this case, the best procedure is to take flat fields immediately before and after each science exposure in the same way as you would take arcs.

When preparing flat-field frames for your data ensure that a **dekker** size (length) larger than that used for the science exposures is used—avoid order overlap in the image, though. This ensures that a reasonable **flat-field** is available across the complete profile of each order. If a choice of gratings is available, use the one which will give you the widest order separation.

In some areas of the échellogram the brightness of a single flat-field may fall off or vary rapidly due to the characteristic spectrum of the **arc lamp** used or variations in the efficiency of the detector (some front-illuminated CCDs have 20–30% variations in efficiency over a small wavelength band). There are two ways to overcome these effects: use a different lamp to produce the flat field in those orders—but usually a different lamp is not available—or, obtain as many unsaturated flat fields as possible and sum or average them.

It may not always be necessary to flat field; a flat-field frame taken with a modern CCD can be flat in response to only a few percent. You may only need to flat field if the signal-to-noise ratio you require is particularly high. The precise figures will depend upon several factors, and should be estimated for each science object.

3.4 Order Tracing

Accurate determination of the path of the échelle orders across the images is vital to achieving the best extractions. Processing software requires a bright, clean (*i.e.*, cosmic-ray free) image from which to trace the orders.

For well-exposed continuous spectra the object frame can be used for tracing. However, in the case of faint objects, or objects with strong absorption features in their spectra, tracing of object frames will not be easy. A **flat-field frame** can be used for tracing as this is likely to give a good signal. Therefore, if necessary, obtain a few flat fields with a narrow **dekker** to improve the traces. It may be worth having *several* possible frames for tracing—in case some of them are badly contaminated by cosmic rays and so difficult to use.

3.5 Wavelength Calibration

As with the CCD characterisation frames, wavelength-scale reference (arc) frames should be taken **bracketing** the science exposures *if* precise wavelength scales are required. At the high **dispersions** used in échelle spectrographs a small change in the optical system can lead to a detectable shift between the bracketing images. Using both arc spectra, a time-weighted mean wavelength scale can be produced and applied to the science data.

3.6 Flux Calibration

Existing standard star data is often based upon a system in which the band size is much larger than the wavelength coverage of a single échelle order. In practice, this can make the application of proper flux calibration to high-resolution échelle spectra difficult or infeasible. Proper high-resolution spectral standards are now starting to become available (notably for **HST**). If you intend to flux calibrate your data you should ensure that suitable standards are available.

Refer to §4.9 for more information on the problems associated with flux calibration.

4 The Basics of Echelle Data Reduction

Figure 2 is a flow chart which maps out the main steps in the échelle data reduction process. ECHMENU is a menu-driven program in which each of the natural steps in the reduction process is handled by a task. This is the top-level menu presented by ECHMENU:

- | | |
|--|-----------------------------------|
| 0. HELP/HYPER (ASCII or hypertext help). | |
| 1. Start a reduction. | 16. Check trace consistency. |
| 2. Trace orders. | 17. Post-trace Cosmic Ray locate. |
| 3. Clip fitted traces. | 18. Image cosmic ray pixels. |
| 4. Determine dekker/object extent. | 19. Quick-look Extraction. |

- | | |
|--------------------------------|------------------------------------|
| 5. Model flat field. | 20. Check wavelength scales. |
| 6. Model sky. | 21. Scrunch and merge multiple. |
| 7. Model object profile. | 22. Model scattered light. |
| 8. Extract orders 1-D. | 23. ADJUST tuning parameters. |
| 9. Locate arc line candidates. | 24. Set single-order operations. |
| 10. Identify features. | 25. Set all-order operations. |
| 11. Flatten order shape. | 26. DISABLE an order. |
| 12. Scrunch to linear scale. | 27. PLOT reduction arrays. |
| 13. Model/Extract orders 2-D. | 28. Full MENU. |
| 14. Save reduced data. | 29. System (\$) commands. |
| 15. Plot order traces. | 30. Output balance-factor frame. |
| | 31. EXIT (alias Q/E/QUIT/EXIT/99). |

In this section each of the major steps is outlined and some of the important and perhaps tricky considerations are mentioned. Most of the steps are similar to those which would be used for extraction of a single-order spectrum, plus a few additional elements to deal with the multiple orders. The handling of cosmic-ray removal is described separately at the end of this section as there are several different approaches to the problem.

4.1 Image Preparation

Most échelle data will be obtained using a CCD to record the image. Careful preparation of the CCD data prior to attempting extraction of spectra is essential. In this Guide the basic procedures are outlined (very!) briefly. Those points relevant to échelle data reduction are included.

The basic steps in the preparation are:

Generate bias frame Typically done by finding the median of several frames taken at the telescope.

Generate flat-field frame Again, done by finding the median of several frames taken at the telescope. Before taking the median of the frames, the median bias frame and a zero-offset constant are subtracted (see below).

Subtract bias frame The median bias frame is subtracted from each arc frame and each object frame.

Subtract zero-offset A selected area of the CCD **overscan region** is used to find the ‘zero-level’ of the camera electronics. This is usually a number in the range 20–200 ADU. The median value of the selected region should be used (to avoid cosmic-ray contamination). This constant value is then subtracted from every pixel in the CCD image.

Crop images Regions—such as the overscan—are not used during the extraction process and should be removed (the same as cropping a photograph) as they may confuse some of the algorithms in the échelle data reduction engine. Very often CCD images will have ‘rough’ edges, *i.e.* non-useable data, which should also be trimmed off at this point.

Depending on your source data and choice of reduction software you may need to:

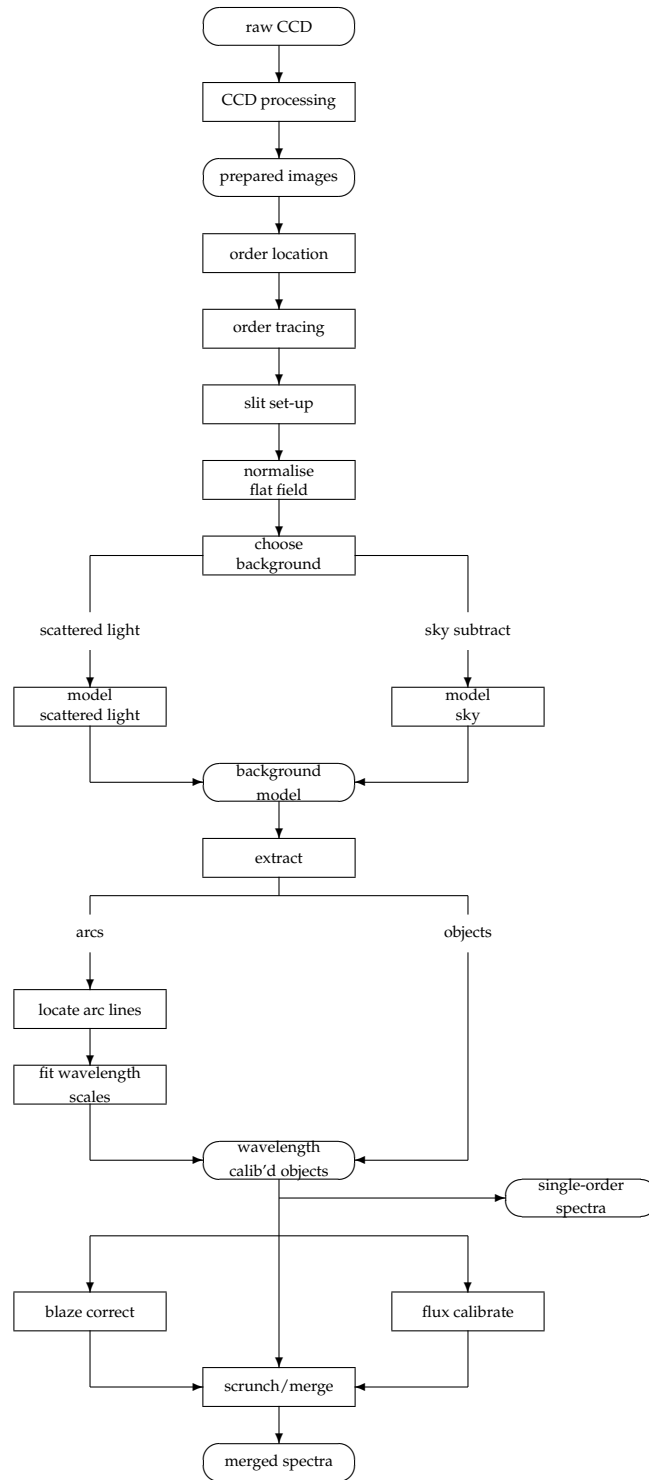


Figure 2: Outline of the échelle data reduction process.

Rotate and orient the image All the major packages constrain the orientation of the échelle orders in some way. The images may have to be adjusted to meet these constraints. In general, if the échelle orders in your data run roughly horizontally (parallel to the X-axis) and the wavelength increases from left to right you will be alright. In other situations, you may need to use some image utilities to re-orient the data. This may involve rotating and perhaps reflecting the images.

You may have data which contain ‘dead columns’ or few-pixel hot-spots. Handling of these is discussed in the documentation for the CCD data preparation packages.

Once the set of arc and object images have been prepared in this way the échelle data reduction process can begin.

4.1.1 Software for CCD Data Preparation

There are quite a few different packages for preparing CCD data. All these packages offer similar functionality. You’ll probably find that it’s easiest to use the preparation package which complements the échelle reduction software you choose, *e.g.*, `noao.imred.ccdred` for IRAF `doecslit`. There are two popular Starlink packages which you might use, FIGARO and CCDPACK. CCDPACK includes some tools for conveniently managing the preparation of many frames and supports error propagation.

4.2 Order Location

Order location is simply the process of finding the approximate position of each of the orders in an échelle image. You can select which of the located orders should then be extracted. This saves time if there is no useful data in some of the orders. Location is achieved by taking a slice across the dispersion direction which when plotted appears similar to the graph in Figure 3.

This example is a section across an IUE é image. You can see about 60 orders are present in this case. In practice, the section across the image will use data from several columns (in the case of a roughly horizontal dispersion), rather than a single column.

4.3 Order Tracing

Once the required orders have been selected the next step is to determine the path of each of them across the image. This process is *order tracing*. Typically the tracing procedure will involve sampling each order in steps along the dispersion direction. The reduction program will attempt to estimate the centre of the order at each sample point. Once an order has been traced in this way you will have the option to fit a curve to the sample data. If all is well, the curve should represent the true path of the order across the frame. In practice, some of the sample points may have to be ignored to get a good fit. This is particularly the case if the trace frame is strongly contaminated with cosmic rays, if the orders are not very bright, or if the spectrum being traced contains strong absorption features.

If many images are taken with the same spectrograph configuration it may well be possible to use a single trace frame for all the extractions.

Figure 4 shows a polynomial (solid line) fitted to the sample points (dots) of a single échelle order.

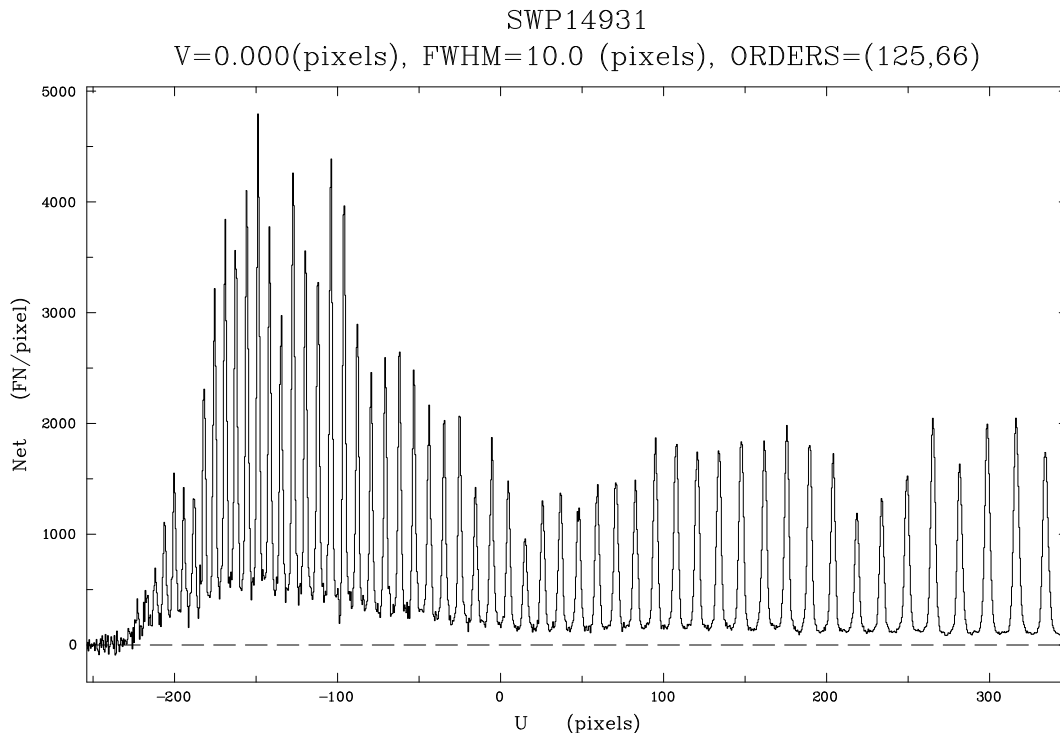


Figure 3: Order Location: cross-dispersion section through an IUE échelle spectrum.

4.4 Slit Definition

In each order of an échelle spectrogram an image of the spectrograph **slit** is projected onto the final image. The physical length of the slit is determined by the **dekker**. In a **flat-field frame** the entire slit should be illuminated, and so the length of the projected image (in the dispersed direction) will be limited by the dekker setting. (The dekker setting should be made sufficiently small that adjacent orders don't overlap in the spatial direction.)

Using a flat-field frame we can determine which pixels on the detector lie inside the projected slit and which pixels lie outside the slit. A reduction program will use the previously determined order traces to build a **cross-dispersion** profile of each order in the frame. These profiles can then be used to decide where the 'software' dekker limits are.

Once the 'software' dekker has been set, the object frame is inspected in a similar way, this time to choose which pixels should contribute to the signal from the object and which (if any) are sky (or 'local') background. Figure 5 shows a typical plot during object and background definition using the ECHMENU program. This procedure leads to a pair of pixel-selecting masks—sometimes called channels—one marking the object, one marking the sky background. If there is a sky signal present in the spectrum it is advisable (if possible) to select pixels on both sides of the object spectrum to contribute to the sky signal. Refer to the next subsection for more information on handling of the background signal.

In the above procedures it may be satisfactory to use dekker/object profiles determined using data from all the orders in the spectrum. This will depend on the nature of the object spectrum

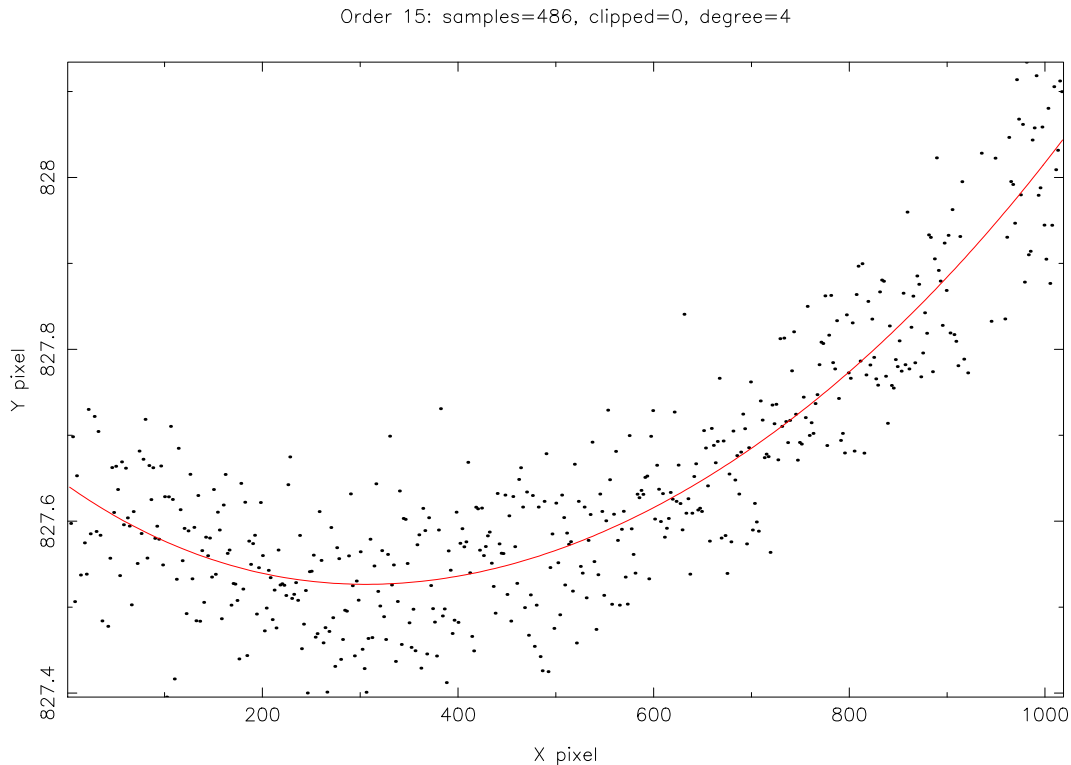


Figure 4: Order Tracing: Fitting a polynomial to an order trace in ECHMENU.

and the chosen extraction method. Basically, if the spatial profiles are similar in all the orders then a single set of profiles can be used. If there are significant order-to-order variations in the profile then some or all of the orders will have to be profiled separately. To be useful, the optimal extraction method requires an accurate cross-dispersion profile.

4.5 Flat Fielding

The flat-fielding of échelle data is handled in different ways by the major reduction packages. The resulting spectra should, however, be essentially the same.

The flat-fielding process removes pixel-to-pixel variations in the response of the detector and any interference fringes (due to either the detector electrode structure or internal reflections in thinned detectors).

Statistical extraction methods (such as optimal extraction) require that the flat field be normalised to remove the colour of the lamp used.

IRAF and MIDAS both provide tasks for the preparation of normalised flat-field frames (respectively, `noao.imred.echelle.apflatten` and `flat/echelle`). These frames can be viewed in the same way as any other image. ECHOMOP can use such a normalised flat-field frame, or the normalised apertures can be computed by ECHOMOP and stored within the *data reduction structure*.

Normalised flat-fields are generated by fitting a polynomial to the shape of each order along the dispersion direction and, in some cases, fitting polynomials to the profile in the spatial direction

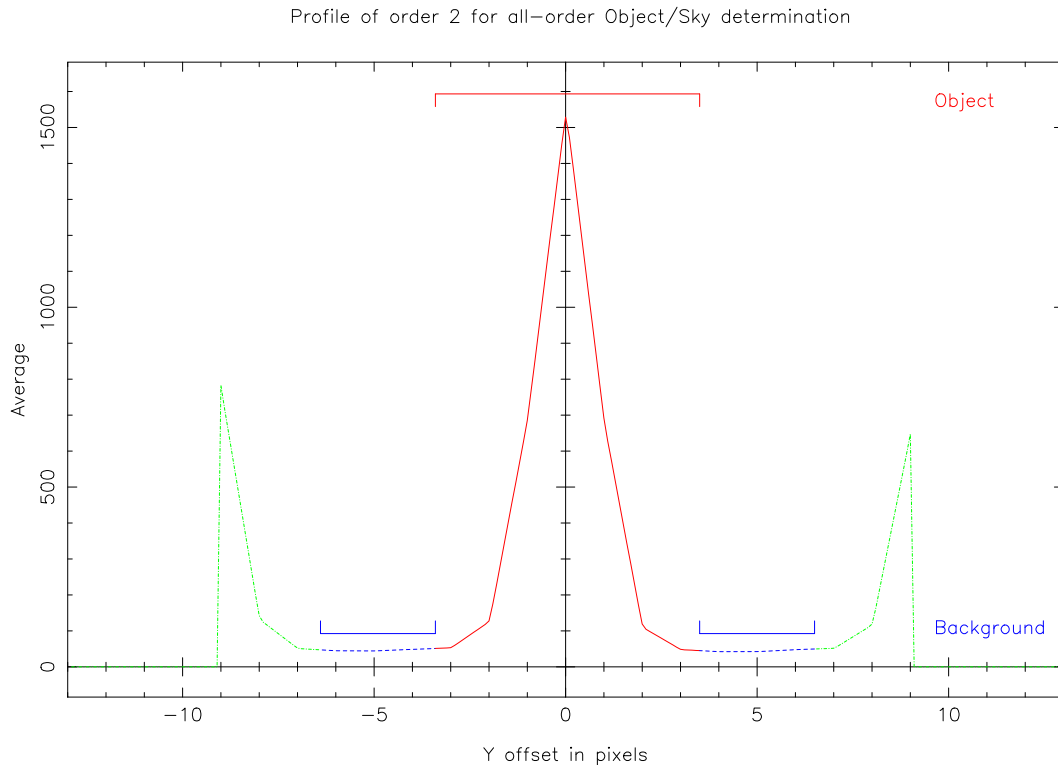


Figure 5: Slit Definition: Selecting the object and background channels in ECH-MENU.

as well. Pixels in any inter-order gaps—where there will be no signal—are set to a value of one in the normalised flat-field.

4.6 Background Handling

The background signal in an échelle image consists of:

- A constant offset from the CCD output processing electronics.
- An optional pedestal produced by pre-flashing the CCD to overcome charge transfer inefficiency at low-signal levels.
- The thermally generated CCD dark signal.
- General scattered light.
- Diffuse light in the inter-order space from adjacent orders.
- Sky background.

The first two contributions are removed in the CCD data preparation phase. The signal due to **dark current** is usually small for short (the order of minutes) exposures in cryogenically-cooled CCD systems.

There are two approaches to determining the background signal level in an échelle image (three if you include not bothering with any background subtraction). These are: use the sky pixels as determined previously in the ‘slit definition’ step or, use a surface fitted to the inter-order background over the whole image. In many cases the first method will be adequate, however, sometimes a suitable background channel cannot be defined. An example of this is an image in which the signal from the object channel of one or more orders has spread out into the inter-order area, perhaps to the extent that some of the orders overlap in the spatial direction. In such a case it may be better to construct a global model for the background over the whole image, rather than trying to use inter-order background channels which are contaminated with light from the object or from an adjacent order. Figure 3 shows how the short-wavelength orders (left-hand side) of an IUE spectrum start to overlap—the inter-order background has clearly risen in this region.

Even if no sky background signal is present in the échelle image it may still be acceptable to use background channel masks as defined in the ‘slit definition’ step. In this case the channels should be selected to lie in the inter-order gaps and so sample the scattered light.

The fitting of a single surface to the background over the whole image is a computationally intensive process and so should be avoided except for those cases where no useable local background can be determined.

4.7 Extraction of Spectra

Having produced a set of models for our data we can proceed to the extraction of the spectral information in the image.

In previous steps we have produced models of:

- The path of each order across the image.
- The profile of the object spectrum in each order.
- The background signal: either globally for the whole image or for each order.

There are several approaches to the extraction of the spectral data. The most commonly used are the *optimal*, and *linear* (sometimes called ‘normal’ or ‘simple’).

Linear extraction is simply the integration of all pixels selected in the profiling step with equal weighting. The corresponding signal in the background channel is subtracted. The disadvantage of this method (as compared to optimal extraction) is that no attempt is made to allow for the fact that pixels at the edges of the order profile contain a smaller part of the signal than those in the middle of the order profile. These pixels will consequently have smaller signal-to-noise ratio and should carry reduced weighting for the ‘best’ possible extraction. Linear extraction is less computationally demanding than weighted extraction methods and is useful for checking data quickly or situations where it is not possible to prepare the data for optimal extraction (*e.g.*, you don’t have the CCD **readout noise** details).

Optimal extraction is designed—in theory at least—to achieve the best possible signal-to-noise ratio with CCD spectral data. The method uses the Poisson statistics of photons, information about the CCD signal processing electronics transfer function, and the modelled profile for the object to weight contributions to the signal. To use the optimal extraction method you will need

to know the **readout noise** and **gain** for the CCD camera used to obtain the spectra. The main limitation of optimal extraction algorithms is the requirement that the spatial profile of the object is a smooth function of wavelength. This means that optimal extraction is unlikely to be useful if spatial (cross-dispersion) resolution is required and/or the spatial profile of the object varies rapidly with wavelength, as for objects with spatially-extended emission-line regions.

Optimal extraction only gives significant improvements over linear extraction at low signal-to-noise levels. However, it has the advantage that the profile models can be used to reject cosmic rays which are incident upon the object or background channels.

There are other extraction weighting-schemes available, refer to §5 for information.

The extraction process is applied to both arc spectra and any standard-star spectra, as well as to object spectra.

4.8 Wavelength Calibration

From the preceding extraction step we have a set of data frames sometimes called *collapsed* échelle spectra. For each object or arc CCD frame we have a three-dimensional dataset: order, sample number and intensity. (You may also have variance information for each sample of each order.) Sample number is simply an index for each integration bin along the order (*e.g.*, the X-axis in Figure 6). The next step in the reduction process is to attempt to determine the relationship between wavelength and sample number for these data.

The basic steps here are:

- Look at the arc (or comparison) spectrum and try to identify features of known wavelength.
- Fit a low-order polynomial to the arc wavelength-sample relation.
- Paste the wavelength-sample relation from the comparison spectrum to the object spectrum.

The wavelength-sample relation can be fitted separately for each order (1-D solution) or a model for the whole échellogram can be built (2-D solution). The success of the latter technique will depend to some extent on how many lines you can identify and where they lie in the spectrum.

Which ever reduction software you choose to use, you should find that a list of spectral feature wavelengths for common arc reference lamps is available on-line (refer to the package documentation for details). You may also be able to lay your hands on a hardcopy of a ‘mapped’ **comparison spectrum** for your selected **arc lamp**, perhaps obtained using the same spectrograph as your data. For example, *UCLES Spectrum of the Thorium-Argon Hollow-Cathode Lamp* should be available at most UK Starlink sites (a **UES** version is also available). This document also gives the free spectral range and wavelength coverage for each order of the UCLES which can be used to estimate the wavelengths in other orders once you have identified features for your first order—the same trick can be used for other instruments if you have similar data available. Some people prefer the ESO arc-line atlas in which the line wavelengths are more clearly printed: *An Atlas of the Thorium-Argon Spectrum for the ESO Echelle Spectrograph in the $\lambda\lambda$ 3400–9000Å Region*.

Ideally each order to be fitted should contain at least three or four identifiable spectral lines, preferably with one close to each end of the order and one or more spread in the middle of the

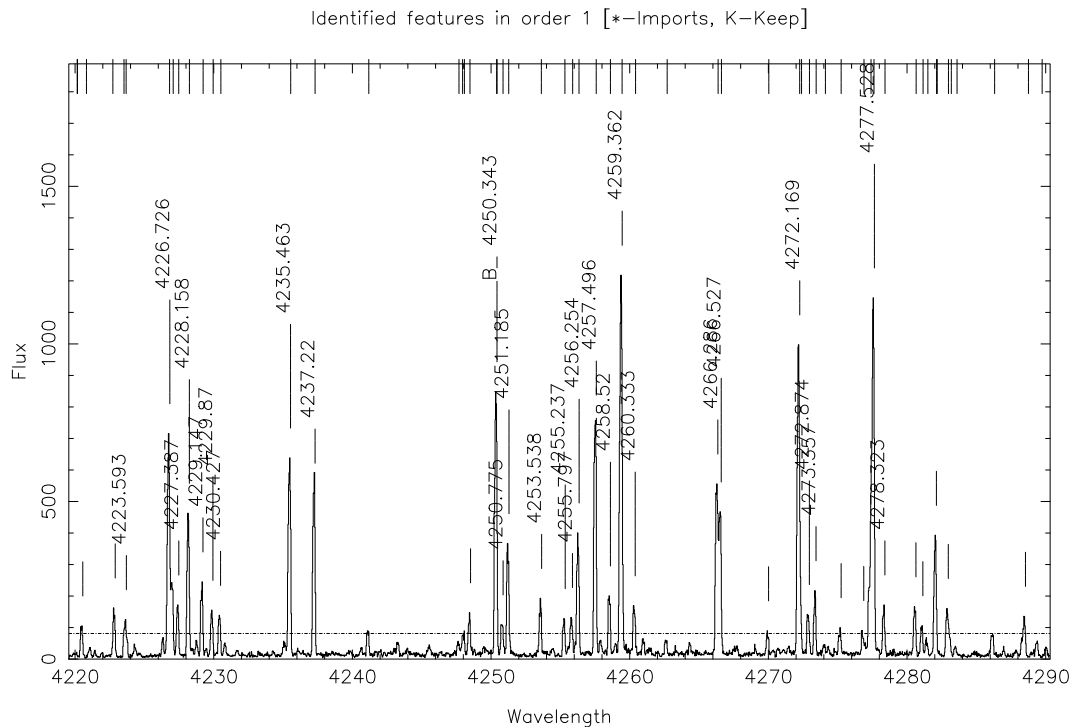


Figure 6: Line Identification: typical plot during interactive fitting with ECHMENU.

order. For some orders it may be useful to refer to the object and/or reference star spectra to look for strong features of known, or approximately known, wavelength. These can be used to help you ‘home-in’ on other features in the arc spectrum for that order. When a fit is made to these features you will be advised of the goodness-of-fit, usually in the form of a plot of line versus deviation-from-fit or RMS deviation values for each line. You will be able to adjust the fit parameters and reject any lines which seem so deviant that they have been mis-identified, then re-fit the data.

Figure 6 shows a plot of a single order during interactive line-identification using ECHMENU.

If attempting a 2-D solution to the wavelength relation for your data you should 1-D fit at least three or four orders before trying a 2-D fit. In a similar manner to the 1-D fits, you’ll get the best result if you use an order at each end of the échellogram and one or more from the middle.

Once you have a complete wavelength-calibrated comparison spectrum you can ‘copy’ the wavelength scale onto your object spectra. It may be useful to calibrate *two* arcs which **bracket** the object exposure in time. This will show any time-dependent variation in the wavelength scale. If there is some change (and it is reasonably small) you can take a time-weighted mean of the two bracketing wavelength scales and use this for the object spectrum. A method for applying this technique with ECHOMOP-reduced data is given in the *Echelle Data Reduction Cookbook* (SC/3).



Figure 7: Blaze correction: the top spectrum is the blaze-corrected version of the lower spectrum. Note that the flux values in the uncorrected order have been scaled and shifted for this plot.

4.9 Finishing Reduction

It may be the case that a set of wavelength-calibrated, individual-order spectra is suitable for your scientific purposes. At this point, you can also perform flux calibration or correct for the **blaze function** (a **grating**-dependent variation in the brightness along orders). You might also want to combine the individual orders into a single spectrum and/or re-bin the data onto a fixed-step wavelength scale.

4.9.1 Blaze Correction

The per-order normalised flat-field models generated earlier can be divided into extracted order spectra to remove the blaze function of the échelle. This can aid the process of fitting line profiles as instrumental effects are removed.

Figure 7 shows a plot of a single-order spectrum and a blaze-corrected version of the same order.

4.9.2 Flux Calibration

An alternative to applying the **blaze correction** is to fully flux-calibrate the data. As mentioned earlier, there may not be reference standards of sufficiently small band-pass size to enable a useful flux calibration to be applied. In échelle spectra a velocity difference between the reference

standard and the object can lead to an effective change in the band-pass wavelength which invalidates the calibration—particularly where strong features are present in the spectrum.

You will probably have to apply a correction for observation of the object and standard star through differing air masses.

The flux calibration process is conceptually straightforward: the object and standard star spectra are summed in the same pass bands as the reference tables. The correction factors can then be calculated by comparing the standard star spectrum with the reference tables.

4.9.3 Re-binning Spectra—Scrunching

Use of a fixed bin of the spectra allows spectra from separate exposures to be co-added. There are many options for the re-binning of the data to a fixed wavelength scale. Two basic options are: bin to a fixed wavelength interval, or bin to a fixed velocity interval. The latter is equivalent to using a logarithmic wavelength scale.

Scrunching the data is equivalent to applying a filter to the data. You might want to investigate the possibility of applying different weighting schemes during the binning process. For example, FIGARO SCRUNCH offers both simple linear interpolation and a quadratic option.

4.9.4 Combining Orders—Merging

Once individual échelle orders have been **blaze-corrected** and scrunched to a fixed-bin wavelength scale they can be combined into a single spectrum. This process might also involve combining spectra from different exposures to overcome dropouts due to **cosmic-ray hits** *etc.*

Although there are plenty of utilities available for splicing together spectra, the best option here is to use one of the merging utilities included in an échelle data reduction package. This will allow you to apply a weighting strategy in the regions where the wavelength coverage of orders overlaps; *e.g.*, ignore data where one order is much fainter than the other, use flux-weighted mean *etc.*

4.10 Handling Cosmic Rays

In the previous descriptions cosmic rays have only been occasionally mentioned. The successful reduction of échelle data requires careful attention to be paid to the location and handling of **cosmic-ray hits** in the data. There are several strategies for the detection of cosmic rays, here are some of them:

Inspection by eye This is the simplest method—display an image and you will probably be able to see some cosmic-ray hits. This is less useful for object frames than, say, **dark frames** as real data can appear similar to a cosmic-ray hit.

Median Filtering Two median filters are applied to each image; one along rows, one along columns. These are then divided into the original image and a histogram of the result is produced. If there are lots of cosmic-ray hits in the image then a clear cut-off point in the histogram will be visible. Pixels above the threshold can be flagged as cosmic-ray hits.

Profile Modelling This technique can be applied in several ways. Most commonly it is implemented as part of the optimal extraction of spectra. Essentially, by constructing a profile of the ‘real’ science data, unexpected—*i.e.*, statistically unlikely—cosmic-ray hits can be found, even when they fall on the spectrum itself. This method can require a large amount of processing time for a large échelle image.

Comparison of ‘Identical’ frames This is another simple method. It can be used where you have several frames of the same object taken in the same configuration. A median image can be generated and pixels which deviate strongly from the median are probably cosmic-ray hits. This method works best when the images are all of the same exposure time.

Depending on the particular frame involved it may be possible to interpolate across a cosmic-ray hit. The alternative is to simply flag the cosmic-ray pixels found so that they are not used in the spectrum extraction.

You should ensure that cosmic rays in your CCD **bias**, **dark**, and **flat-field** frames are removed prior to attempting reduction—a median filter is suitable. It is particularly important that cosmic rays do not severely degrade the frame used for order tracing—otherwise the whole reduction will be unsuccessful.

Once slit-definition is complete any bright pixels lying outside the slits are almost certainly cosmic-ray hits.

Some implementations of the optimal spectrum extraction method allow you to select whether profile-based cosmic-ray rejection is applied during the extraction process (as is the norm) or post-extraction (*e.g.*, ECHOMOP).

Whichever cosmic-ray removal/flagging strategy you choose to adopt, it is wise to check the results by displaying the original image with detected events flagged—sometimes bright sky lines can be mistakenly flagged as cosmic-ray events.

5 Data Reduction Facilities

Like any form of data reduction, there are as many ways of handling échelle spectra as there are people doing it. This section introduces some of the échelle data reduction packages available and offers advice on selecting the package most suitable for your work.

5.1 Available Packages

There are three substantial packages designed for the general reduction of échelle data; the IRAF ECHELLE package, the MIDAS ECHELLE context and the Starlink ECHOMOP package. The main packages offer similar facilities including the ‘optimal’ extraction of spectral data. FIGARO can also be used to do complete échelle data reductions but most of the routines available have been superceded by ECHOMOP.

5.1.1 STARLINK—ECHOMOP

ECHOMOP development was funded specifically for the reduction of data from the AAT coude échelle spectrograph UCLES. The author made the package sufficiently flexible that it can be used for reduction of data from other instruments.

Part of the package is an interactive menu interface, echmenu, which guides you through the steps of a reduction. The individual tasks required for a reduction can alternatively be accessed from the user's preferred command shell.

The package provides a complete set of tasks for échelle data reduction. CCD-related processing is *not* included and must be done using a suitable package (*e.g.*, CCDPACK or FIGARO). echmenu guides you through the complete reduction process covering; order location, order tracing, slit definition, flat-fielding, sky background subtraction or scattered light modelling, extraction, and wavelength calibration. Input/output data are held in Starlink NDF format files. Internal data are held in a *reduction structure* which is an ECHOMOP-specific format HDS file.

ECHOMOP has facilities which include: an automated arc-line-location algorithm, interactive plotting of intermediate data, automated cosmic-ray location and removal, and full propagation of variance data through an extraction.

The ECHOMOP user may use a package such as FIGARO to perform flux calibration.

The internal ECHOMOP reduction file keeps all the housekeeping data for a particular reduction in one place. This means a reduction can be stopped and resumed at the same point without difficulty. A 'cloning' system is provided which allows template data from previous reductions to be inherited by similar, new reductions.

The documentation for ECHOMOP is in two primary sources; a paper document *ECHOMOP—Echelle data reduction package* (a Starlink User Note) which is also available in hypertext form, and on-line HELP.

The on-line help for ECHOMOP is available in two formats: a simple hypertext version accessed using a Web browser (*e.g.*, Mosaic or Netscape) and a standard Starlink HELP library. The help text is very thorough including algorithm descriptions and detailed parameter details.

ECHOMOP is supported by the Starlink Application Programming team.

ECHOMOP provides three extraction weighting schemes:

- **Simple.**
Weights all object pixels equally.
- **Profile weighted.**
Weights each pixel by $P(i, j)^2$ where $P(i, j)$ is the calculated normalised profile at spatial offset j (sub-sampled) from the trace centre and i is the column number.
- **Optimal.**
Weights each pixel by the product of the calculated profile $P(i, j)$ and an estimate of the uncertainty of the pixel intensity.

5.1.2 IRAF—ECHELLE/DOECSLIT

IRAF contains a set of tasks for échelle data reduction in the package `noao.imred.echelle`, the extraction being carried out by the main task `doecslit`. This is a ‘mature’ software package in that it has not undergone significant changes in recent IRAF releases.

The software inherits its user interface from IRAF and as such should be easy to use for those familiar with the IRAF shell `c1`, parameter entry and editing, and IRAF image file handling.

An IRAF task similar to `doecslit`, `dofibers`, with instrument-specific variants is available. This task is quite similar to `doecslit` except that the aperture for each object must be individually defined.

Facilities to carry out all the procedures required for reduction of échelle data are provided. Initial processing of CCD images is done using tasks in `noao.imred.ccdred`. These tasks are also used in the flat-field generation process. `doecslit`, which is an IRAF script, guides a user through the data reduction process carrying out; sky background or scattered light subtraction, extraction, wavelength calibration, and flux calibration (if needed). Data are input/output in 2- or 3-dimensional IRAF images.

There is no special facility provided for merging of the orders from an échellogram into a single spectrum, the `scombine` task provides a simple facility for merging the orders.

Parameters required for flux calibration (relating to the position of the observatory) must be provided by the user with non-NOAO data (*i.e.*, most UK astronomers) using the `observatory` task. Suitable extinction data are also required.

Data processing with `doecslit` can be interrupted and restarted without a problem. The pattern of one data processing run can be inherited by another run to speed up common or similar reduction tasks.

The `echelle` package has a full documentation set in the same style as other IRAF packages. On-line help describing the tasks and the parameters for each are available and accessible from the IRAF `c1` shell.

The paper document *A User’s Guide to Reducing Echelle Spectra With IRAF* is an excellent introduction to the processing of échelle data using IRAF. Pointers to other IRAF documents relevant to the inexperienced user are included. This document works through the steps of a reduction (flat-field, order location, extraction, wavelength calibration) in enough detail to get users started. Use of related tasks for plotting the data—of which IRAF has many—is described.

`doecslit` usage and parameters are documented in *Guide to Slit Spectra Reduction Task DOECSLIT*. This is the paper reference document for the task.

IRAF is supported by a team at NOAO.

`noao.imred.echelle`, supports two extraction weighting schemes:

- **None.**
Weights all object pixels equally.
- **Variance.**
An alternative name for the *optimal* extraction weighting method. Scheme weights each pixel by the product of the calculated profile $P(i, j)$ and an estimate of the uncertainty of the pixel intensity.

5.1.3 MIDAS—CONTEXT ECHELLE

ESO MIDAS provides a suite of commands and options for the reduction of data from échelle instruments. The software is contained within the MIDAS context ECHELLE.

In a similar manner to the IRAF tasks in `noao.imred.echelle`, the MIDAS ECHELLE context inherits command and parameter style from the host environment.

Like `noao.imred.echelle`, a full range of facilities for échelle data reduction are provided. The processing of CCD data into a format suitable for the ECHELLE context to work with is carried out using other tasks from MIDAS. ECHELLE provides a set of about 30 commands arranged in five procedures to carry out the reduction. Facilities for order location, extraction, wavelength calibration, and instrument response correction are provided. Data can be read from **FITS** or **IHAP** formats only. MIDAS tables are used at some stages in the reduction process (*e.g.*, wavelength calibration).

Although the MIDAS échelle data reduction software is primarily intended for processing data from ESO instruments (*e.g.*, CASPEC on the 3.6m telescope), it can be adapted to process data from other instruments.

The documentation for MIDAS is integrated in a three volume set which includes information about the ECHELLE context. Within the documentation are three areas particularly relevant to ECHELLE, these are:

- Chapter 7 of Volume B (Data Reduction), *Echelle Spectra*.
This contains outline descriptions of some of the algorithms used, pointers to other documents and some technical description of the MIDAS tables used by the context.
- Appendix D of Volume B, *Echelle Reduction*.
This is a guide suitable for use by MIDAS novices, covering all basic aspects of a data reduction run.
- Appendix D of Volume C, *Standard Reduction Commands Context: echelle*.
This is the reference document for the tasks and parameters used by the context.

The MIDAS Users Guide Volumes A and B are now available in a hypertext form (converted from \LaTeX source) at the central ESO Web server. Volume C which is the unified on-line help text can be accessed via the MIDAS GUI `xhelp` at an installation.

As part of MIDAS, the échelle data reduction tasks are supported by the team at Garching.

Three extraction weighting schemes are available:

- **Linear.**
Weights all object pixels equally.
- **Average.**
Uses a weighting $1/L$ where L is the length of the slit.
- **Optimal.**
Weights each pixel by the product of the calculated profile $P(i, j)$ and an estimate of the uncertainty of the pixel intensity. Algorithm based on paper by Mukai (1990).

5.2 Choosing a Package

The three packages briefly described above can meet most échelle data reduction requirements. There are, however, other factors to be considered with basic functionality *etc.*

Here's a table which lists some useful commands for each of the three packages mentioned previously:

The availability of a package is important—it may be difficult to get started with a package not already available at your site—don't let this put you off, but be aware that some effort may have to be expended before you start to work with any data. If you are already an expert at the IRAF c1 then you may get 'up-to-speed' more quickly with the IRAF échelle package as compared to learning a new environment from scratch. Similarly, it may be useful to use a package which a local colleague is already familiar with—ask to look over their shoulder next time they're using the package.

It is worth considering the format of the data that you will receive from the observatory. Most data will be provided in FITS format. Most software (all the above) can read FITS data. (To get FITS information to a format accessible by ECHOMOP you should use KAPPA FITSIN or FITSDIN.)

Bear in mind that if you intend to propagate variance information from the processed échelle data you may be restricted in the choice of software. ECHOMOP supports the output of data with variance information in a format which other Starlink software can read (NDF) at each stage of the reduction process. The available conversion utilities for switching between IRAF/FITS and NDF formats will not normally propagate variance data in an immediately usable way—or even at all—in some cases.

A point worth considering is the provision of bad-pixel masks. ECHOMOP allows the individual pixels to be excluded from an extraction by reference to the quality component of an NDF. In IRAF you will have to interpolate across any cosmic rays *etc.*, prior to performing the extraction.

IRAF commands are from the noao.imred.echelle package unless otherwise stated.

Starlink commands are part of ECHOMOP unless otherwise stated.

All MIDAS commands are accessible once set/context echelle has been done.

Task	IRAF	STARLINK	MIDAS
Rotate image	images.rotate	FIGARO IROT90 KAPPA ROTATE	ROTATE/ECHELLE
Subtract constant from image	images.imarith	FIGARO ICSUB KAPPA CSUB	COMPUTE/IMAGE
Divide images pixel-by-pixel	images.imdivide	FIGARO IDIV KAPPA DIV	COMPUTE/IMAGE
Generate median of several images	noao.imred. ccdred.combine	FIGARO MEDSKY	AVERAGE/IMAGES
Order location	apfind	ech_trace	SEARCH/ORDER
Order tracing	aptrace	ech_trace ech_fitord	DEFINE/ECHELLE DEFINE/HOUGH
Slit definition	apdefault apedit	ech_spatial ech_profile	DEFINE/HOUGH
Normalise flat field	apnormal apflatten	ech_ffield	FLAT/ECHELLE + COMPUTE/IMAGE
Model scattered light	apscatter	ech_mdlbck	BACKGROUND/ECHELLE
Model per-order 'sky' background		ech_sky	DEFINE/SKY + EXTRACT/SKY
Extract	apsum	ech_extrct	EXTRACT/ECHELLE
Locate arc lines	ecidentify	ech_linloc	SEARCH/ECHELLE
Fit wavelength scales	ecidentify	ech_idwave	IDENTIFY/ECHELLE
Blaze correct flux calibrate	continuum calibrate	ech_blaze FIGARO SPFLUX	RIPPLE/ECHELLE RESPONSE/ECHELLE
Scrunch		ech_scrunch	REBIN/ECHELLE
Merge	scombine	ech_mulmrg	MERGRE/ECHELLE

6 Glossary

- **ADU**
Literally, Analogue-to-Digital Units. These are the raw numbers which emerge from a digitiser—the “counts” per pixel read out from a CCD.
- **Arc lamp**
A lamp which burns with a characteristic spectrum which is used as a reference or comparison for the wavelength scale of a spectrum.
- **AAO/AAT**
Anglo-Australian Observatory / Anglo-Australian Telescope.
- **Bias frame**
An image generated from several raw CCD frames taken with no light incident upon the detector and of ‘zero’ exposure time.
- **Blaze, blaze angle**
Literally, *to cut* in this context. Arises from the nature of some **gratings** where the grooves are non-symmetrical to concentrate the incident light in one or several orders on one side of the zero order of the image.
- **Blaze correction**
Process of normalising each order in an échelle spectrum to remove the brightness variation due to the blaze angle. Sometimes called ripple removal or simply normalisation.
- **Bracketing**
A term from photography. Simply means taking reference exposures before and after the ‘main’ exposure **bracketing** it in time. Can be used to apply to a pair of series of exposures taken before and after science data. For example, arc frames, flat-field frames *etc.*, are usually collected both before and after observing to allow any time dependency to be found and, at least to a first order, compensated for.
- **Centroiding**
Process of estimating the true position of the centre of a spectral order in the spatial direction, where the shape of the profile of the order can be predicted and the profile is under-sampled.

A similar process occurs in **IPCS** cameras to locate photon “events” (usually with sub-pixel accuracy).
- **Collimator**
Optical element which produces a light beam in which the rays are (at least very nearly) parallel.
- **Comparison Spectrum**
A spectrum from a known source, typically an **arc lamp**, used as a reference for the modelling of the wavelength scale of spectra.
- **Cosmic-ray hit**
Extra signal present in CCD images due to the incidence of a cosmic ray on the detector

during an integration. Cosmic-ray hits appear as bright spots, usually occupying only a few pixels on the detector. (Unless the ray is travelling nearly parallel to the surface of the detector in which case a streak may be produced.) In spectroscopy cosmic-ray identification is a particular problem as real features in a spectrum can similarly occupy only a few pixels in the image.

The most effective method of detection is to take two or more exposures of the same spectrum in the same instrument configuration and compare them or take a median.

- **Cross-dispersion**

The direction perpendicular to that in which a spectrum is dispersed. In an échelle spectrograph a *cross-dispersing* optical element is used to separate orders in the direction perpendicular to the dispersion.

- **CCD**

Charge-Coupled Device. For astronomy, the most commonly used optical imaging sensor.

- **CCDPACK**

A Starlink package for the preparation of CCD data for reduction. Includes tools for managing the processing of large numbers of images. Described in SUN/139.

- **CONVERT**

A Starlink utility package for converting between different image formats. Described in SUN/55.

- **Dark current**

Electrons released in a detector (often a CCD) by the action of the thermal energy of the body of the detector.

- **Dark Frame**

An exposure taken with the shutter closed. Typically, the exposure time used is similar to that selected for the object frames in an observing run. Dark frames give an estimate of the background level due to **dark current** in a CCD.

- **Dekker**

A fork-shaped part of the slit assembly of a spectrograph which sets the length of the slit. This limits the size of the light beam in the direction perpendicular to the spectrograph dispersion.

- **Dispersion**

A measure of the 'power' of a spectrograph. A dimensionless number, typically given in \AA mm^{-1} . This number arises by dividing the true length of a section of an order in the output image (in the dispersion direction) by the wavelength range covered.

Also the act of splitting light into its components by wavelength.

- **DIPSO**

A self-styled "friendly spectral analysis program" in widespread use in the community. Described in SUN/50.

- **DST**

A data format used by early versions of FIGARO. The CONVERT utility provides facilities for translating DST files to NDF.

- **Echelle**
Literally, from the French, *Ladder*. A **grating** in which the lines are ruled much further apart than those of an ordinary diffraction grating. This gives the échelle a very high resolution over a short wavelength range when the high orders are used.
- **ESO**
European Southern Observatory.
- **FIGARO**
A general astronomical data reduction package. Available in several flavours. The Starlink version is described in SUN/86.
- **FITS**
Flexible Image Transport System. The most commonly used format format for astronomical image data storage.
- **Flat field, flat fielding**
A **flat field** is one illuminated with some uniform source. Used to determine the relative sensitivity of the elements (pixels) in a system.
Flat fielding is the process of dividing by a normalised flat-field to remove the sensitivity variations of a system.
- **Free Spectral Range (FSR)**
The part of an échelle order spectrum which “belongs” to that order, *i.e.*, the wavelength range over which this order is the brightest of the orders in the échellogram.
- **Gain, Output transfer function**
The number of **ADU** counts per electron (*i.e.* per photon) in the output signal from a CCD camera.
- **Grating, diffraction grating**
Optical element ruled with (usually) thousands of fine parallel lines which produce interference patterns when light is incident upon them. Can be used as the main dispersing element in a spectrograph.
The equation $m\lambda = d \sin \theta$ describes the diffraction pattern produced by the grating. Where: m is the order number, λ is a selected wavelength, d is the rule spacing, and θ is the angle of incidence of light.
- **GHRS**
Goddard High-Resolution spectrograph. An instrument on the Hubble Space Telescope.
- **Halation**
A term originally used in photography to denote the process by which the image in a developed emulsion is spread beyond the bounds of the incident light. Is used to describe the spreading of light from one order to the next in an échelle spectrogram.
- **HST**
Hubble Space Telescope.
- **IDS**
Intermediate Dispersion Spectrograph. An instrument at the ING.

- **IHAP**
An image format used by MIDAS. This format is available for input to MIDAS for backward-compatibility with some of the data acquisition systems at the La Silla Observatory.
- **ING**
The Isaac Newton Group of telescopes at the RGO on La Palma.
- **INT**
Isaac Newton Telescope at the La Palma Observatory.
- **IPCS**
Image Photon Counting System. A common optical image sensor, has zero **readout noise** and good blue response.
- **IRAF**
Image Reduction and Analysis Facility.
- **ISIS**
A twin spectrograph at the WHT. The two ‘arms’ are optimised for response in the red and blue regions of the optical waveband.
- **IUE**
International Ultraviolet Explorer.
- **JKT**
Jacobus Kapteyn Telescope at the La Palma Observatory.
- **KAPPA**
The Starlink Kernel Application Package. A suite of facilities for processing and viewing astronomical images. Described in SUN/95.
- **MIDAS**
Munich Image Data Analysis System. A complete package for the handling of astronomical data written and maintained by a team at ESO.
- **NDF**
The Standard Starlink data storage format. An hierarchical format for multi-dimensional data storage. Accessed using libraries supported by Starlink. NDF is described in SUN/33.
- **NOAO**
National Optical Astronomical Observatories.
- **Order separation**
The gap between adjacent orders in an échelle image. There is a compromise between the spectral range covered and the distance between orders. (If the orders are close together more fit on the detector and so a larger spectral range is covered.) When working with non-starlike objects a larger order separation is desirable otherwise the signal from adjacent orders may overlap.
- **Overscan, overscan region**
The action of clocking a raster sensor (*e.g.*, CCD) for more cycles than the number of signal collection sites in the detector line. This leads to additional ‘empty’ pixels in the row as

read out from the detector. On an image display this will appear as a band along the edge of the image, the **overscan region**. Used to determine the zero-point of the analogue circuit of the camera, *i.e.*, for no signal input to the system from the detector.

- **Periscope(s)**
Optical arrangement which feeds light (usually from the sky background) into the slit of a spectrograph. These can be used when the object being observed would otherwise fill the slit and so no sky signal would be recorded.
- **Prism**
Usually, a wedge-shaped optical element which disperses light passing through it. The name arises from the Greek *prisma prismatos*, 'thing sawn' (well that's what it says in the dictionary anyway...)
- **Quantum Efficiency, QE**
The ratio of the number of photoelectrons produced to the number of photons incident upon a detector. CCDs have QEs of about 50% or greater at optical wavelengths.
- **RAL**
Rutherford Appleton Laboratory. The Starlink project is run from RAL.
- **Readout noise**
In this context, usually means the signal measured for no input signal for a detector such as a CCD.
- **Resolution**
The difference in wavelength between two (notional) features which can be just distinguished in the spectrum.
- **Resolving power**
The value $\lambda/\Delta\lambda$ where λ is the wavelength at some point in a spectrum and $\Delta\lambda$ is the resolution at that wavelength.
- **Scan, scanning**
Process of determining the approximate position of orders in a spectral image. In the case of échelle spectra this allows you to select which orders you wish to extract.
- **Slit**
Usually narrow entry point for light to a spectrograph. The slit is often made from a pair of ordinary razor blades which can be machined to achieve very straight edges. This gives a precisely determined light source for the instrument.
- **Spectrograph**
An instrument for separating and recording the spectral components of light. Contemporary instruments use electronic cameras to record the spectra.
- **Starlink**
UK national network of computers for astronomical data reduction and the organisation which manages the network.
- **Stray light**
Light which arises within an instrument due to reflections from surfaces not intended to act as optical elements.

- **SDF**
Starlink Data File. A file with the extension `.sdf` accessible via Starlink software or libraries.
- **STSDAS**
Space Telescope Science Data Analysis System. A package written for **HST** data reduction, closely integrated with **IRAF**.
- **Template, order**
A description of the position of spectral orders in an image as determined by tracing the orders. The traced orders in one image being used to predict the position of the orders in a second image taken with the same instrumental configuration.
- **Template, reduction**
A set of commands and/or parameter values which are appropriate for a general type of data reduction operation. Usually in the form of a *data reduction script* which can be quickly tailored for a particular reduction task.
- **Throughput**
A measure of the overall efficiency of an optical system. For optical telescope/spectrograph combinations this will be of the order of a few to tens of percent.
- **Tracing**
The Process of finding the path of a spectrum or order of a spectrum across an image frame.
- **UCLES**
University College London Echelle Spectrograph. A medium-resolution instrument in the coudé room at the **AAT**.
- **UES**
Utrecht Echelle Spectrograph. Northern hemisphere 'twin' of the UCLES at the WHT, has a different control system but similar optical design.
- **UHRF**
Ultra-High Resolution Facility of the UCLES. An (up to) diffraction-limited resolution spectrograph for the **AAT**. Uses some of the optics of the UCLES.
- **VICAR**
Literally *Video Image Communication and Retrieval*. A format used for some images notably those for most data from the **IUE** satellite.
- **VLT**
Very Large Telescope. Usually refers to the ESO VLT, but can also refer to very-large telescopes in the general sense.
- **WHT**
William Herschel Telescope. 4.2m telescope at the RGO on La Palma.
- **Zero subtraction**
Process of the removal of the instrument zero-signal level as determined by measuring the signal in the **overscan region** of a CCD image.

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