The Heterodyne Data Reduction Cookbook
1.2
Abstract

This cookbook provides a short introduction to Starlink facilities, especially \texttt{SMURF}—the Sub-Millimetre User Reduction Facility—and \texttt{KAPPA}—the Kernel Application Package—for reducing, displaying, and analysing ACSIS data. In particular, this cookbook illustrates the various steps required to reduce the data; and gives an overview of the ORAC-DR pipeline which carries out many of these steps using a single command. Specialised pipeline recipes are discussed. The cookbook also introduces cube analysis with the \texttt{GAIA} display tool, and spectral analysis with \texttt{SPLAT}. 
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<td>Auto-Correlation Spectrometer and Imaging System</td>
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<td>ARD</td>
<td>ASCII Region Definition</td>
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<td>CADC</td>
<td>Canadian Astronomy Data Centre</td>
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<tr>
<td>CSO</td>
<td>Caltech Submillimetre Observatory</td>
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<tr>
<td>FITS</td>
<td>Flexible Image Transport System</td>
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<td>FWHM</td>
<td>Full-Width at Half-Maximum</td>
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<tr>
<td>GAIA</td>
<td>Graphical Astronomy and Image Analysis Tool</td>
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<td>HDS</td>
<td>Hierarchical Data System</td>
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<td>JCMT</td>
<td>James Clerk Maxwell Telescope</td>
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<td>LSB</td>
<td>Lower sideband</td>
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<td>MSB</td>
<td>Minimum Schedulable Block</td>
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<td>NDF</td>
<td>Extensible N-Dimensional Data Format</td>
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<td>HARP</td>
<td>Heterodyne Array Receiver Programme</td>
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<td>QA</td>
<td>Quality Assurance</td>
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<td>RxA</td>
<td>Receiver A</td>
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<td>SAMP</td>
<td>Simple Application Messaging Protocol</td>
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<td>SDF</td>
<td>Starlink Data File</td>
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<td>S/N</td>
<td>Signal-to-Noise ratio</td>
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<td>USB</td>
<td>Upper sideband</td>
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<td>WCS</td>
<td>World Co-ordinate System</td>
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<td>WVM</td>
<td>Water Vapour radioMeter</td>
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Chapter 1
Introduction

1.1 This cookbook

This cookbook is designed to instruct ACSIS users on the best ways to reduce and visualise their data using Starlink packages.

This guide covers the following:

- Chapter 1 - Computer resources and software you’ll need before getting started.
- Chapter 2 - Starlink basics—tools for exploring your data.
- Chapter 3 - Heterodyne observing at the JCMT.
- Chapter 4 - Naming convention and examining raw ACSIS data.
- Chapter 5 - The ACSIS pipeline and recipes explained.
- Chapter 6 - How to run the pipeline.
- Chapter 7 - Regridding your data with makecube.
- Chapter 8 - Analysing your reduced cube.
- Chapter 9 - Advanced analysis techniques such as changing co-ordinate frames.
- Chapter 10 - Using GAIA to analyse your data.
- Chapter 12 - Getting your data from CADC.

Style convention
In this cookbook the following styles are followed:

- % represents the command-line prompt.
- Command-line examples are shown in navy typewriter font.
- Parameters, FITS keywords, parameters and their values are presented in typewriter font.
- The names of Starlink commands appear as in san serif font.
- The names of commands, menu items, tabs, or buttons within graphical tools (such as GAIA or SPLAT) appear like this.
- The names of windows produced by graphical tools appear "like this".
- The names of attributes appear like StdOfRest.
- Useful tips or reminders are given in outlined boxes.

1.2 Before you start: computing resources

Before reducing heterodyne data you should consider whether you have sufficient computing resources for your data. That said, there can only be vague guidelines because resource usage depends on many factors, such as the spatial area and resolution, the number of observations being reduced together, observing and bandwidth modes (see Section 3.3), and the number of subbands. However, the main factor is the volume of data being processed concurrently.
The ORAC-DR pipeline can demand approaching 300 GB of peak storage for the largest (about a degree square) HARP maps, and at least 24 GB of memory during spectral-cube creation. For more-normal-sized maps of individual targets, say 20 square arcminutes from your observations, would only require about 10 GB of storage and most modern computers would have sufficient memory. The storage requirements can more than double if all intermediate files are retained for diagnostic purposes; intermediate files are normally removed at the end of each pass through a recipe. Reducing manually permits you to tidy files as you move along, but is very time consuming.

Reducing RxA data and HARP stares or small jiggle maps is undemanding of resources.

1.3 Before you start: Starlink software

This manual utilises software from the Starlink package: SMURF [5], KAPPA [8], GAIA [10], ORAC-DR [4], CONVERT [6], CUPID [1], CCDPACK [11], and PICARD [12]. Starlink software must be installed on your system, and Starlink aliases and environment variables must be defined before attempting any ACSIS data reduction. You can download Starlink from the Starlink webpage.

Below is a brief summary of the packages used in this cookbook and how to initialise them. Note that all the example commands are shown within a UNIX shell.

1.4 Options for Reducing your Data

You have three options for processing your data:

(1) performing each step manually,
(2) write your own scripts, or
(3) running the automated pipeline.

The automated pipeline is recommended for new users of JCMT heterodyne data or those unfamiliar with the Starlink software. The pipeline approach works well if your project is suited to using one of the standard recipes, as are most projects. Running the pipeline is probably essential if you have a lot of data to process. To use the science pipeline, skip straight to Chapter 5.

Performing each step by hand allows more fine-tuned control of certain processing and analysis steps, although some fine-tuning is available in the pipeline via recipe parameters (see Section 6.2).

Once you have determined your optimal parameters you can pass them to the pipeline or a script. Chapter 7 and Chapter 8 discuss the manual approach.

While you have the option of running the pipeline yourself, you can find pipeline reduced files for individual and co-added observations by night in the JCMT Science Archive (JSA).

These have been reduced using the ORAC-DR pipeline with the recipe specified in the MSB or with the Legacy Survey recipe. Principal investigators (PIs) and co-investigators (co-Is) can access these data through the JSA before it becomes public by following the instructions in Section 12.
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<th>Description</th>
<th>Initialise</th>
<th>Help</th>
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<td>SMURF</td>
<td>The Sub-Millimetre User Reduction Facility (SMURF) contains \texttt{makecube} that will process raw ACSIS data into spectral cubes.</td>
<td>%smurf</td>
<td>%smurfhelp</td>
</tr>
<tr>
<td>KAPPA</td>
<td>A general-purpose applications package with commands for processing, visualising, and manipulating NDFs.</td>
<td>%kappa</td>
<td>%kaphelp</td>
</tr>
<tr>
<td>CONVERT</td>
<td>CONVERT allows the interchange of data files to and from NDF. Other formats include IRAF, FITS, and ASCII.</td>
<td>%convert</td>
<td>%conhelp</td>
</tr>
<tr>
<td>CUPID</td>
<td>CUPID is a package of commands that allows the identification and analysis of clumps of emission within one-, two- or three-dimensional data arrays</td>
<td>%cupid</td>
<td>%cupidhelp</td>
</tr>
<tr>
<td>ORAC-DR</td>
<td>The ORAC-DR Data Reduction Pipeline \cite{4} is an automated reduction pipeline. ORAC-DR uses SMURF and KAPPA (along with other Starlink tools) to perform an automated reduction of the raw data following pre-defined recipes.</td>
<td>%oracdr_acsis</td>
<td>SUN/230</td>
</tr>
<tr>
<td>PICARD</td>
<td>PICARD uses a similar pipeline system as ORAC-DR but for the post-processing of reduced data. While mainly implemented for SCUBA-2 data, there are a few recipes that are heterodyne compatible. See Appendix A for more details and a description of the available recipes.</td>
<td>%picard RECIPE</td>
<td>SUN/265</td>
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<tr>
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<th>Description</th>
<th>Open</th>
<th>Help</th>
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<td>GAIA</td>
<td>\textsc{Gaia} is an interactive image and data-cube display and analysis tool. It incorporates tools such as source detection, three-dimensional visualisation, clump visualisation, photometry, and the ability to query and overlay on-line or local catalogues.</td>
<td>%gaia</td>
<td>SUN/214</td>
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<td></td>
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<td></td>
<td>SC/17</td>
</tr>
<tr>
<td>HDSTRACE</td>
<td>This tool lets you examine the contents of Starlink data files.</td>
<td>%hdstrace</td>
<td>SUN/102</td>
</tr>
<tr>
<td>SPLAT</td>
<td>\textsc{Splat} is a graphical spectral-analysis tool. It can also interact with the Virtual Observatory.</td>
<td>%splat</td>
<td>SUN/243</td>
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Chapter 2
Good to know: Starlink

2.1 File format

Starlink routines run on HDS files (Hierarchical Data System) which normally have a .sdf extension (Starlink Data File). HDS files can describe a multitude of formats. The most common HDS format you will encounter is the NDF (N-Dimensional Data Format). This is the standard file format for storing data which represent N-dimensional arrays of numbers, such as spectra, images, etc. The parameter files discussed in Section 2.3 are also HDS format.

Raw data retrieved from the JCMT Science Archive comes in FITS format. For information on converting between FITS and NDF see Appendix B.

2.2 Parameters

Parameters control the behaviour and data processed in Starlink applications. A parameter expects a value that is one of the following types: string, boolean, integer, or single- or double-precision floating point. You can either specify parameter values on the command line or in response to prompts. Most parameters have sensible defaults leaving you to concentrate on the main parameters. Parameter usage is described in a tutorial.

2.3 How to find the current parameter values

A directory called adam is created in your home-space by default when you run Starlink applications. In this directory you will find HDS files for each of the application that you have run. These files contain the parameters used and results returned (if appropriate) from the last time you ran a particular application.

You can specify a different location for the adam directory by setting the environment variable ADAM_USER to be the path to your alternative location. This is useful when running more than one reduction to avoid interference or access clashes.

To see the ADAM parameters, run HDSTRACE on any of the parameter files. For example, to see which parameters were used and the results from last time you ran stats, you can type the following from anywhere on your system:

```
% hdstrace ~/adam/stats
```

This will report the following

```
STATS <STRUC>
  ADAM_DYNDEF <DEFAULTS> {structure}
  COMP <_CHAR*132> 'DATA'
```
You can see `stats` was run on the data array with ordered statistics as well as the resulting values. Any of the parameters returned by running `HDSTRACE` on an ADAM file can be extracted using the command `parget`. In the example below, the mean value from the last instance of `stats` is printed to the screen.

```bash
% parget mean stats
```

### Tip

Try not to exit from Starlink tasks by breaking in, since this may corrupt the parameter file (reported as an integrity check error). If this happens delete the parameter file. Enter `!!` at a prompt if possible to have a clean exit.

### 2.3.1 Extracting a value for scripting

`parget` is designed to make life easier when passing values between shell scripts. In the C-shell scripting example below, the median value from `histat` is assigned to the variable `med`. Note the use of the back quotes.

For more information on scripting our work see Appendix C.

```bash
set med = 'parget median histat'
```

If the parameter comprises a vector of values these can be stored in a C-shell array. For other scripting languages such as Python, the alternative vector format produced by setting parameter `VECTOR` to `TRUE` may be more appropriate. Single elements of a parameter array may also be accessed using the array index in parentheses.

In addition to running `hdstrace` on the ADAM file, you can find a list of all parameter names that can be returned with `parget` in the [KAPPA manual](#) under ‘Results Parameters’ for the command in question. Note that these names may be different from the names returned in a terminal when running application.

### 2.4 How can I view the metadata?

There are two [KAPPA](#) tasks which are extremely useful for examining your metadata: `fitslist` and `ndftrace`, which can be used to view the FITS headers and properties, such as dimensions, of the data respectively. The third option is the stand-alone application `HDSTRACE`.

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<th>ORDER</th>
<th>&lt;_LOGICAL&gt;</th>
<th>TRUE</th>
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<td>MAXIMUM</td>
<td>&lt;_DOUBLE&gt;</td>
<td>36.666870117188</td>
</tr>
<tr>
<td>MAXWCS</td>
<td>&lt;_CHAR*132&gt;</td>
<td>'10.625136, -0.381122, -6.057133'</td>
</tr>
<tr>
<td>MINWCS</td>
<td>&lt;_CHAR*132&gt;</td>
<td>'10.720136, -0.017795, -31.05713'</td>
</tr>
<tr>
<td>MEAN</td>
<td>&lt;_DOUBLE&gt;</td>
<td>0.25890738014562</td>
</tr>
<tr>
<td>MINIMUM</td>
<td>&lt;_DOUBLE&gt;</td>
<td>-2.7510244846344</td>
</tr>
<tr>
<td>SIGMA</td>
<td>&lt;_DOUBLE&gt;</td>
<td>0.72429928153974</td>
</tr>
<tr>
<td>.. .. ..</td>
<td>.. .. ..</td>
<td>.. .. ..</td>
</tr>
<tr>
<td>.. .. ..</td>
<td>.. .. ..</td>
<td>.. .. ..</td>
</tr>
</tbody>
</table>
fitslist This lists the FITS header information for any NDF (raw or reduced). This extensive list includes dates & times, source name, observation type, band width, number of channels, receptor information, exposure time, start and end elevation and opacity. In the example below, just the object name is extracted.

% fitslist file | grep OBJECT

Likewise, if you know the name of the keyword you want to view, you can use the fitsval command instead, for instance

% fitsval file OBJECT

ndftrace ndftrace displays the attributes of the NDF data structure. This will tell you, for example, the units of the data, pixel bounds, dimensions, world co-ordinates (WCS), and axis assignations.

% ndftrace map fullframe fullwcs

An NDF can contain more than one set of world co-ordinates. The fullwcs parameter requests that all sets be listed rather than the currently chosen one.

hdstrace hdstrace lists the name, data type and values of an HDS (Hierarchical Data System) object. The following example shows the structure of a time-series cube, including the pixel origin of the data structure. To show just the first $x$ lines of values for each parameter include the option nlines=x on the command line:

% hdstrace file nlines=3

Otherwise to see all the lines and information that is available in each extension use nlines=all. The example below displays all the system temperature values and pipes the result to ‘less’ to make viewing easier.

% hdstrace file.MORE.ACISIS.TSYS nlines=all | less

You can see it descends two levels (into MORE and ACSIS) to retrieve the information. Other information available at this level include receptors and receiver temperatures.

Full details of ndftrace and fitslist can be found in the KAPPA manual. Details on HDSTRACE can be found in the HDSTRACE manual.

Tip

The .sdf extension on filenames is not required when running Starlink commands.

2.5 What has already been done to the data?

If you are presented with a data file you may wish to see what commands have been run on it and, in the case of a co-added cube, which data went into it. Two KAPPA commands can help you with this:
hislist The **KAPPA** command `hislist` will return the history records of the NDF.

```bash
% hislist myfile brief
```

Including the `brief` option returns a simple list of the commands. Omitting this will include the text associated with each command and can be useful for finding out what parameters were used in each case. This works for all NDFs including those reduced by the pipeline, for these all the commands executed as part of the pipeline reduction script will be listed. The version of software used for each step is also reported.

provshow The **KAPPA** command `provshow` displays the details of the NDFs that were used in the creation of the given file. It includes both immediate parents and older ancestor NDFs.

```bash
% provshow file
```

### 2.6 How to examine, process or extract a subset of your data

For all Starlink commands you can specify a sub-section of your data on which to run an application. You do this by appending the bounds of the section to be processed the NDF name. This may be on the command line or in response to a prompt.

The example below runs `stats` on a sub-cube within your original cube. This sub-cube is defined by bounds given for each axis. The upper and lower bounds for each axis are separated by a colon, while the axes themselves are separated by a comma. Note that the use of quotes is necessary on a UNIX shell command line, but not in response to a prompt or in many other scripting languages.

```bash
% stats 'cube(10.5:10.0,0.0:0.25,-25.:25.)'
```

The bounds are given in the co-ordinates of the data (Galactic for Axes 1 and 2 and velocity for Axis 3). You can find the number and names of the axes along with the pixel bounds of your data file by running `ndftrace`. In the example above the ranges are 10.5° to 10° in Longitude (note the range goes from left to right), 0° to 0.25° in Latitude, and -25 to +25 km s\(^{-1}\) in velocity. To leave an axis untouched simply include the comma but do not specify any bounds.

**Tip**

Be careful to give world co-ordinate values in floating point. Integers are interpreted as pixel indices.

To define your bounds in FK5 co-ordinates use the following format.

```bash
% stats 'cube(22h18m:22h32m,05d:05d30m,)
```

To write a section of your data into a new file (called `newcube.sdf` in the example below) use `ndfcopy` with bounds.

```bash
% ndfcopy 'cube(10.5:10.0,0.0:0.25,-25:25)' newcube title="l=10.5 sub-section"
```
Here the option `title` defines a title for the new cube which replaces the title derived from the original.

You can also define a region as a number of pixels from a given origin. The example below extracts a 25×25 pixels cube around the position $l = 10^\circ$, $b = 0^\circ$.

```plaintext
% ndfcopy 'cube(10.0~25:0.0~25,)' newcube
```

**Tip**

To help identify your sub-region in pixel co-ordinates, open your file in [GAIA](https://www.gaia.de) and change the built-in co-ordinates to PIXEL via *Image-Analysis > Change coordinate > Built-in coordinates.*
## 2.7 How to get help

<table>
<thead>
<tr>
<th>Command</th>
<th>Description</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>showme</td>
<td>If you know the name of the Starlink document you want to view, use showme. When run, it launches a new web page or tab displaying the hypertext version of the document.</td>
<td>% showme sun95</td>
</tr>
<tr>
<td>findme</td>
<td>findme searches Starlink documents for a keyword. When run, it launches a new web page or tab listing the results.</td>
<td>% findme kappa % findme heterodyne</td>
</tr>
<tr>
<td>docfind</td>
<td>docfind searches the internal list files for keywords. It then searches the document titles. The result is displayed using the UNIX more command.</td>
<td>% docfind kappa</td>
</tr>
<tr>
<td>Run routines with prompts</td>
<td>You can run any routine with the option prompt after the command. This will prompt for every parameter available. If you then want a further description of any parameter type ? at the relevant prompt.</td>
<td>% makemap prompt % REF - Ref. NDF /!/&gt; ?</td>
</tr>
</tbody>
</table>
Chapter 3

JCMT Heterodyne Observing

3.1 Spectral-line Observing

Submillimetre instruments use heterodyne techniques to observe spectral lines at high resolution. Heterodyne receivers take a weak incoming signal and mix it with a reference frequency known as the local oscillator (LO). This results in a signal of lower (intermediate) frequency (IF) which can be amplified and more easily sampled. The current JCMT receivers have an IF of 4 GHz (RxA) or 5 GHz (HARP). This mixing produces two frequencies for each value of the LO ($\nu_{\text{sky}} = \nu_{\text{LO}} \pm \nu_{\text{IF}}$) which are known as the upper sideband (USB) and lower sideband (LSB).

In a single-sideband receiver one of these is suppressed. Double-sideband receivers have the two frequencies superimposed.

Reducing the noise in the system is crucial to the efficiency of these receivers. The required integration time is directly proportional to the total noise in the system given by $T_{\text{sys}}$ via the radiometer formula

$$T_{\Lambda}^{\text{rms}} = \frac{2 T_{\text{sys}} \kappa}{\sqrt{\Delta \nu t}}$$

where the terms are as follows:

- $\Delta \nu$ is the frequency resolution of each channel.
- $t$ is the total integration time (time spent integrating on the source and the reference position).
- $\kappa$ is the telescope specific backend degradation factor.
- The factor of 2 is required for position-switch or beam-switch observations where half the time is spend off source at the reference position. For frequency switched observations it is 1.414 instead.
- $T_{\text{sys}}$ is the system temperature in kelvin and describes the total noise of the system. It includes contributions from the background sky temperature, the Earth’s atmosphere, ground spillover picked up by the side lobes and the noise from the receiver itself (known as $T_{\text{R}}^{\text{rms}}$). $T_{\text{R}}^{\text{rms}}$ can be determined by measuring the effects on $T_{\text{sys}}$ when looking at hot and cold loads, where the cold load is black-body source.
- $T_{\Lambda}^{\text{rms}}$ is the rms value of the noise observed in the spectrum in kelvin.

Tip

Both $T_{\text{sys}}$ and $T_{\text{R}}^{\text{rms}}$ are stored in the raw data files. This information is stored in the .MORE.ACSIS.TSYS and .MORE.ACSIS.TRX extensions respectively, and can be viewed using HDSTRACE (see Section 2.4).
3.2 Heterodyne Instruments

The heterodyne instruments described below are those currently operational on the JCMT. For information on previous instruments see the JCMT web pages.

In the following $\eta_{MB}$ is the main-beam efficiency and $\eta_{fss}$ is the forward spillover and scattering efficiency. For the latest and historical calibrations visit [ACSIS Beam Efficiencies](#).

3.2.1 RxA3 Frontend

Receiver A3 (RxA3) is a single-element double-sideband receiver. It operates in the A-band between 211 and 276 GHz. In addition to stare observations, the most common observing mode for RxA3 is raster mapping. In 2016 RxA3 was updated to RxA3M. The instrument was retired in 2018.

<table>
<thead>
<tr>
<th>Receiver</th>
<th>FWHM</th>
<th>$\eta_{MB}$</th>
<th>$\eta_{fss}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RxA3</td>
<td>19''</td>
<td>0.57</td>
<td>0.80</td>
</tr>
</tbody>
</table>

RxA3M has an additional calibration step (automatically applied by our pipelines if you use a version after June 2019) to normalise the flux levels of observations between the upper and lower sideband. If you need more control of this in the pipeline, please see the calibration recipe parameters in Appendix G. The older RxA3 also had some variation in flux levels between the sidebands, but we do not have a calibration correction for this.

3.2.2 HARP Frontend

The Heterodyne Receiver Array Programme (HARP) is a 16-receptor array arranged on a $4 \times 4$ grid [3]. It operates in the B-band between 325 and 375 GHz. The receptors are adjacent on the focal plane but separated on the sky by 30 arcseconds (or approximately twice the beamwidth). The footprint of the full array is 2 arcminutes. Note that not all receptors are operational; historically between 12 and 15 receptors have been available at any given time. The tracking receptor is chosen to be the best performing of the four internal ($2 \times 2$) receptors in the grid.

You can find the number of the tracking receptor and the number of working receptors in the FITS header values REFRECEP and N_MIX respectively.

In addition to stare observations with the tracking receptor, the most common observing modes for HARP are jiggles and raster maps. These observing modes are described in Section 3.3 and an example image from each mode is shown in Figure 3.2.

<table>
<thead>
<tr>
<th>Receiver</th>
<th>FWHM</th>
<th>$\eta_{MB}$</th>
<th>$\eta_{fss}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HARP</td>
<td>14''</td>
<td>0.63</td>
<td>0.88</td>
</tr>
</tbody>
</table>

3.2.3 ACSIS Backend

Since 2006 September, the backend for heterodyne instruments has been the Auto-Correlation Spectrometer and Imaging System known simply as ACSIS (see Figure 3.1). Given the various combinations of ACSIS's 32 down-converter modules and available IF outputs from the different instruments, a number of bandwidth modes and corresponding frequency resolutions are available. Listed below are the most common ones. Visit the JCMT web pages for a full list.
<table>
<thead>
<tr>
<th>Subbands</th>
<th>Bandwidth mode</th>
<th>Channel Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>250 MHz</td>
<td>0.0305 MHz (HARP/RxA/RxW)</td>
</tr>
<tr>
<td>1</td>
<td>1000 MHz</td>
<td>0.488 MHz (HARP/RxA/RxW)</td>
</tr>
<tr>
<td>1</td>
<td>1860 MHz (1600,1800)</td>
<td>0.977 MHz (HARP) 0.488 MHz (RxA/RxW)</td>
</tr>
<tr>
<td>1</td>
<td>440 MHz (400,420)</td>
<td>0.061 MHz (HARP) 0.0305 MHz (RxA/RxW)</td>
</tr>
<tr>
<td>2</td>
<td>any 250 MHz</td>
<td>0.061 MHz (HARP) 0.0305 MHz (RxA/RxW)</td>
</tr>
<tr>
<td>2</td>
<td>any 1000 MHz</td>
<td>0.977 MHz (HARP) 0.488 MHz (RxA/RxW)</td>
</tr>
</tbody>
</table>

There are a number of special configurations available with ACSIS. These make use of multiple sub-bands to cover lines at different frequencies. You can find the subsystem number for a given observation by the FITS header SUBSYSNR.

You will find each subsystem number corresponds to a different molecule or transition (given by the FITS headers MOLECULE and TRANSITION). The most common pairings are C$^{18}$O (3-2)/$^{13}$CO (3-2) and DCN (5-4)/HCN (4-3) for HARP, and SiO (60-50)/SO (43-34) for RxA.

Figure 3.1: Front view of ACSIS at the JCMT. Although designed to work with HARP, ACSIS can be used with any JCMT heterodyne receiver.
3.3 Observing Modes

3.3.1 On-source

**Stare** A stare, or sample, observation is as simple as it sounds. When you open reduced cubes of stare observations in GAIA you will see a map consisting of one pixel for each receptor (just one in the case of RxA). The left-hand panel of Figure 3.2 shows a stare observation opened in GAIA. You can also view the central spectrum using linplot (see Appendix F) or SPLAT.

**Jiggle** A jiggle map is a common HARP observing mode. They are designed to fill in the 30′′ spacing between the HARP receptors resulting in a 2′ × 2′ map. This is achieved by ‘jiggling’ the secondary mirror in a 4 × 4 or 5 × 5 pattern to give a HARP4 or HARP5 map respectively. The HARP4 pattern has a 7.5′′ pixels while the HARP5 has 6′′ pixels, slightly under- and over-sampling compared with Nyquist. The central panel of Figure 3.2 shows a HARP5 jiggle pattern.

Each of these patterns can be pixel-centered, where the target co-ordinates fall on one of the central four pixels, or map-centered where the target co-ordinates lie at the centre of the map between the four central pixels. See Figure 3.3 for an illustration of the different jiggle patterns. Although designed for HARP this mode can be used with the single-element receivers.

**Raster** Raster mapping, or scan mapping, is designed for mapping large areas with maximum efficiency. The telescope continuously takes data while scanning across the source. When HARP is used for raster mapping the array is rotated 14°04 to the direction of the scan in order to give a fully sampled map with 7.3′′ pixels. This will result in jagged edges to your reduced map which you may wish to trim. It is common when using HARP to repeat the map scanning along the other axis to give a ‘basket-weave’ pair of maps. Each one of the pair will appear as an individual observation. The right-hand panel of Figure 3.2 shows a HARP raster map.

3.3.2 Reference

**Position-switch** In position-switch (PSSW) mode, the whole telescope moves off source and on to the reference position. This allows a large offset to the reference
Beam-switch  In beam-switch (BSW) mode, the secondary mirror chops onto the reference position. This results in fast and accurate sky subtraction but it is limited to targets which have a blank reference position within 180″ (the maximum chop distance of the SMU).

Frequency-switch  In frequency-switch (FSW) mode the telescope does not move but the centre of the spectral band is shifted, typically by 8 or 16 Mhz, to a line-free region of the spectrum. It is very efficient with no off-source time and can be useful when no emission-free reference position can be found.

Figure 3.3: Top row: HARP4 jiggle patterns produce a map of 16×16 pixels each of 7″5. Bottom row: HARP5 jiggle patterns produce a map of 20×20 pixels each of 6″.

position, useful in crowded environments such as the Galactic Plane. The main disadvantage is that it takes a longer time resulting in less-accurate sky subtraction or non-flat baselines.
3.3.3 **Hybrid**

Subsystems are normally arranged to cover different spectral lines and would be processed independently. However, there is also a mode in which the subsystems overlap in frequency, called hybrid. Such data are combined to yield a broader spectral coverage, say where there multiple lines in proximity. The number of subsystems is a power of two up to a maximum of four.
Chapter 4  
Raw ACSIS Data  

4.1 Data Format  

Raw ACSIS data follow this naming convention:  
\texttt{aUTDATE\_OBSNUMBER\_SUBSYSTEM\_SUBSCAN}  
For example, \texttt{a20131115\_00055\_03\_0001.sdf}. The first ‘a’ represents ACSIS. The UT date and observation number (OBSNUM) serve as an identifier for any given night of observing. ACSIS observations may include up to four frequency settings given by the different subsystems (00-03), while long observations may require multiple subscans to avoid a file size >512 GB.  

4.2 Visualising raw data  

Use the Starlink application GAIA to visualise your raw data. The is initiated by:  
\% gaia rawfile  

Loading a file in GAIA produces two to three windows (see Figure 4.1 and Figure 4.2). The main window shows a map of the HARP receptors (along the $x$-axis; note the 16 pixels) for a given sample of the observation (time on the $y$-axis). You can track the performance of an individual receptor by following a column from bottom to top to check its consistency. In Figure 4.1 H03 is dead for the whole observation. The spectrum for a receptor at one of the time slices can be seen by clicking on the pixel. This will bring up another window—the "Spectral plot" (see Figure 4.3). This spectrum will be replaced when you click on a different pixel.  

You can change the way the data is displayed in the "Display image sections of a cube" window by changing the Axis. Selecting Axis number two will display spectra against time while Axis number three gives spectra against receptors. You can scroll through your data by moving the Index of plane slider.  

A second way to scroll through your spectrum is to click and drag the vertical red bar on the "Spectral plot" window. As you do so array shown in the main window will automatically update.  

You will likely want to change the auto cut of the colour scale, the colour scheme and the zoom factor—all of which are controlled by buttons on the sidebar in the main window.  

See the GAIA manual for full details.  

4.3 Identifying and Masking Bad Data  

You can mask bad receptors in the time-series data with the \texttt{KAPPA} command \texttt{chpix}. In the example below all data for Receptors 7 and 8 (on the second axis) are turned off by setting them to BAD. Note the
Figure 4.1: Initial GAIA windows displayed upon loading a raw data file. The main window on the left shows a map of receptors at given time-samples during the observation. You may have to zoom in multiple times by clicking the large $Z$ button on the side panel. On the right, the "Display image sections of a cube" window enables you to navigate the time axis.

Figure 4.2: Select the NDF from the container file. This window is displayed upon loading a new file in GAIA. In this example, you can choose from NDFs holding the data, the system temperatures, the effective times, and the exposure times.

commas in the SECTION parameter which specify which axis is being referred to; here the first (spectra) and third (time) axes are unchanged so no range is defined. You will have to repeat the command for non-contiguous receptor numbers.

% chpix in=raw out=raw_masked section="',7:8,'" newval=bad

You can also mask a subset of the time stream for a particular receptor. The example below masks out time Steps 18 to 33 for receptor H01. See Figure 4.4 for instructions on how to identify the affected time range.
Figure 4.3: The "Spectral plot" window displaying its time-varying signal, appears automatically once a pixel is clicked in the main window. The vertical red line indicates the time slice that is currently selected in the "Display image sections of a cube" window. This can be dragged across the spectrum to scroll through the spectra. Examine exposure time map etc. in ancillary arrays.

```%
% chpix in=raw out=raw_masked section='’,1:1,18:33’’ newval=bad
%
```

Note that the numbering for the 16 receptors here is 1–16; this is in contrast to 0–15 that you will encounter with the pipeline.

For jiggle maps, where the receptors do not cover multiple sky positions, bad receptors can be identified in the reduced cubes. For raster maps, however, bad receptors are most easily identified in the time-series data. Once you have opened your raw cube in [GAIA](https://www.gaia.nus.edu.sg) it is useful to select the second axis (receptor) which gives spectral dispersion along the $x$-axis and time along the $y$-axis. You can use the cube control panel to step through each receptor looking for bad spectra (see Figures 4.4 and 4.5).
Figure 4.4: The left-hand GAIA window shows the raw data before masking. Clicking on a pixel will show the spectra. The spectrum shown is from receptor H01 at Step 18 (see circled Y value). To mask this receptor in time from Step 18 to 33—at which point the bad baselines disappear—use chpix. The right-hand GAIA window shows the raw data after masking where the time range in question is now blank.
Figure 4.5: In this example, the second axis (receptor number) has been selected. Use the arrows outlined in red on the **Index of plane** bar to scroll through the receptors. Here you can see Receptor 13 (see circled **Index of plane** value) which goes noisy two-thirds the way through the observation.
Chapter 5
The ACSIS Pipeline

The ORAC-DR pipeline [4] is a generic automated data reduction pipeline that can process your raw JCMT data and return advanced data products: baselined single observation cubes, mosaicked and co-added cubes, moments map and clump catalogues. [14]

It has advanced algorithms for the common routines such as baseline subtraction. The data processing is performed using standard KAPPA, SMURF, and CUPID applications, the main ones of which are described in later chapters.

5.1 Recipes and primitives

Reduction recipes in ORAC-DR consist of a series of stand-alone processes, known as primitives. These primitives are linked together to form data reduction recipes. Each primitive can be fed different input data depending on the nature of the recipe in question and may sometimes be omitted altogether.

There are four main science recipes available, each tailored to different type of observation:

- REDUCE_SCIENCE_NARROWLINE
- REDUCE_SCIENCE_BROADLINE
- REDUCE_SCIENCE_GRADIENT
- REDUCE_SCIENCE_LINEFOREST

A summary of these recipes is given below.

There are also variants of the recipes with the following suffixes.

- _POL polarimetry
- _QL Quick Look which merely runs makecube to turn the raw time-series spectra into a spectral cube for display during data acquisition.
- _SUMMIT A limited reduction to keep pace with data acquisition at the JCMT. It excludes any bad spectra rejection, quality assurance, or iterative baseline determination.
<table>
<thead>
<tr>
<th>RECIPE</th>
<th>DESCRIPTION OF EMISSION</th>
<th>BASELINE METHOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>NARROWLINE</td>
<td>One or more narrow lines are expected across the band. Select this recipe if the expected lines are less than about 8 km s(^{-1}) wide.</td>
<td>Smoothing: spatial = 5 × 5 pixels frequency = 10 channels</td>
</tr>
<tr>
<td>BROADLINE</td>
<td>This recipe is designed for wide lines that extend over a large fraction of the band. The line is typically too weak to see in a single observation so a pre-determined baseline window and linear baselines are used.</td>
<td>Uses the outer 10% of each end of the spectra to fit a single-order polynomial.</td>
</tr>
<tr>
<td>GRADIENT</td>
<td>Typically one moderately wide line is expected, for which the center velocity varies significantly across the field. The baseline window changes across the field. Nearby galaxies often fall in this category. The expected lines should be wider than about 8 km s(^{-1}) and probably not wider than 20% of the available bandwidth</td>
<td>Smoothing: spatial = 3 × 3 pixels frequency = 25 channels</td>
</tr>
<tr>
<td>LINEFOREST</td>
<td>A forest of lines is expected across the band. Bright, nearby star-formation sources may fall in this category. This recipe also creates a separate moments map for each line (as defined by the parameter PER_LINE).</td>
<td>Smoothing: spatial = none frequency = 10 channels</td>
</tr>
</tbody>
</table>

### 5.2 The workflow

You can follow this commentary via the flow chart in Figure 5.1.

Two notations are used in the following list:
- **a_cube** to mean the regridded cube of a single observation.
- **g_cube** to mean the group cube which is a co-add of all the a_cube files.

Note that the pipeline will co-add data into a group file whenever it encounters observations with identical LO frequencies, base positions and bandwidths. You can also force a set of observations, such as ones of the same object taken on different nights, to be regarded as a single group to be combined via the oracdr -onegroup command-line option.

1. The raw data is copied to the local directory. Typically, subsystems are treated as individual and separate observations by ORAC-DR except for hybrid-mode observations.

2. Because data acquisition is asynchronous, time slices are not necessarily written in sequential order. The next step sort the time-series data into time order. This makes it easier to search for intermittent bad data.

3. The noisy ends of the spectral band dwarf most astronomical signal, and hence are removed as follows. The spectra are collapsed along the receptor using the ‘sigma’ estimator to form a single spectrum. A constant value background is then fit to the resulting spectrum. The fitting regions are used to determine where the spectrum gets noisier (i.e. higher RMS values in the RMS spectrum). These high-noise regions are then trimmed from the ends in the frequency axis. There is also an alternative to trim specified percentages through the TRIM_recipe parameters (see Table G.2).

4. The DC-level offset between corresponding sub-band observations is determined using the median of all the spectra. The DC offset is then subtracted from the sub-band spectra, and the resulting sub-band spectra are mosaicked together to form single time-series cube.
(5) Regions or individual spectra containing high- and low-frequency interference from local sources are identified and flagged. Bad detectors are identified by comparing the deviation from linearity of each detector’s baseline.

(6) Strong spikes (±150) are replaced by bad values.

(7) Quality assurance checks are run on the raw cubes. See Appendix H for a description of the checks performed. Any time-slices failing any of these checks gets flagged as bad and are not included in the group co-add that follows.

(8) Once all the raw observations have undergone the initial processing, the individual time-series files are combined to form a g_cube.

(9) The g_cube is smoothed by an amount specified by the particular science recipe being used. See Section 5.1 for details on the different recipes.

(10) mftrend is run to find the baseline regions on the smoothed g_cube. The ranges are determined automatically by setting auto=true. A baseline mask is written out.

(11) The baseline mask is then applied to the unsmoothed g_cube and mftrend is re-run. This time however, the emission regions have been masked out, so all remaining data are included in the fit by setting auto=false. The resulting baseline is subtracted.

(12) Moments maps and noise maps are made from the baseline-subtracted g_cube.

(13) If another iteration is required, continue to Step (14). If not, the processing is complete.

(14) The baseline mask is converted back to the time series with unmakecube. There it is applied to the time-series data for each observation.

(15) A baseline is fit to the masked time-series data using mftrend and the result is subtracted from the unmasked time-series data. This can be a higher-order polynomial (up to 15th order), although a linear fit is often used.

(16) A flat field, i.e. the relative responsivties of the detectors, is optionally created and applied. It involves making cubes for each receptor combining all observations on a given date to improve the accuracy. There is a choice of analysis methods, but an iterative approach of thresholding—to exclude the noisy baseline that would dilute the comparisons—worked best on most suitable observations. Those with low signal-to-noise or signal only originating in a small percentage of the area mapped are not amenable to determining the receptor-to-receptor responses. (See (see Table G.5).

(17) An a_cube is made from the baseline subtracted data for each observation.

(18) The individual baseline-subtracted time series are combined to make a new g_cube.

(19) Return to Step (9)
Another observation?

Flag low-frequency interference

Mask bad detectors with bad baselines

Create cube (per subsystem)

Sort time series

Trim high-noise end regions

Merge hybrid modes

Flag high-frequency interference

Yes

Initial Processing

No

Quality Assurance assessment

Copy over raw data

a...raw

a...cube

a...ts

a...em

a...merge

a...hfinmasked

a...lfinmasked

a...bllnmasked

a...thr

a...tmsk

Another observation?

Yes

No
SC/20.2 — The ACSIS Pipeline

Iterative Group Processing

- Create emission-masked time series
  - a...tsmask
- Form cube from ts baseline mask
  - a...cubemask
- Mask baseline regions in time series
  - a...msk
- Fit baseline to masked time series
  - a...tsmsk
- Subtract baselines from unmasked ts
  - a...bl
- Evaluate and apply flat field
  - a...ff
- Make cube from bs-subtracted ts
  - a...reduced
- Make observation moments maps
  - a...integ/iwc
- Make observation noise maps
  - a...noise
- Form group cube
  - g...cube
- Smooth cube (spectral & spatial)
  - g...blmask
- Create baseline region mask
  - g...bl
- Add mask to unsmoothed group cube
  - g...reduced
  - g...integ/iwc
  - g...noise
  - g...rms/rmslo/rmshi
- Fit baselines to group cube
  - g...bl
- Subtract baselines
  - g...reduced
- Make group moments maps
  - g...integ/iwc
- Make group noise maps
  - g...noise
- Quality Assurance assessment
  - g...rms/rmslo/rmshi

Another iteration?
- Yes
- No

Processing complete
Figure 5.1: Flow chart of the processes employed by the ORAC-DR ACSIS pipeline, specifically the REDUCE_SCIENCE_NARROWLINE and REDUCE_SCIENCE_GRADIENT recipes. A few minor processing steps are omitted to avoid the diagram being too long. Other recipes may have additional steps or omit steps as appropriate. Because of space constraints baseline is sometimes abbreviated to ‘bs’ and time series to ‘ts’ in the step descriptions. The prefix and suffix of the file created at each stage is shown to the right of the process box. Note that suffix ‘a’ refers to an individual observation, while ‘g’ refers to a group (or co-added) file.
Chapter 6
Running the pipeline

6.1 Checking and changing the science recipe

You can find out which recipe is set in the data header via the RECIPE keyword in the FITS header of any of your raw files. You can use either of the options below:

```
% fitsval a20130609_00059_01_0001 RECIPE
% fitslist a20130609_00059_01_0001 | grep RECIPE
```

You can override the recipe set in the FITS header by listing any different one on the command line when starting ORAC-DR. For example:

```
% oracdr -file mylist -loop file -log x REDUCE_SCIENCE_GRADIENT
```

6.2 Setting recipe parameters (optional)

You can tailor the recipe parameters by supplying a .ini file (called myparams.ini in the following example). This file contains the recipe name (which must match the one assigned to your data, whether from the header or any different one specified on the command line) followed by the options you wish to specify in the following format:

```
[REDUCE_SCIENCE_NARROWLINE]
MOMENTS_LOWER_VELOCITY = -30.0
MOMENTS_UPPER_VELOCITY = 155.0
PIXEL_SCALE = 6.0,10.0
SPREAD_METHOD = gauss
SPREAD_WIDTH = 9
SPREAD_FWHM_OR_ZERO = 6
REBIN = 2
```

Notice the two values given for the PIXEL_SCALE option. This means that two maps will be produced, one at each of the specified pixel scales. See Appendix for a full list of recipe parameters.

The .ini file can contain an arbitrary number of [] constructs for different recipes, qualified by object name or ORAC-DR internal headers.

While the use of recipe parameters is optional, once you have some experience with the pipeline you are encouraged to tailor the recipe parameters for your reductions to get the best out of the recipe and your data.
6.2.1 Setting recipe parameters by object name

You can further select the recipe parameters by object name, as given by the OBJECT FITS header converted to uppercase with spaces removed. Here are some examples.

```
[REDUCE_SCIENCE_BROADLINE:NGC253]
REBIN = 10.0,20.0,30.0
PIXEL_SCALE = 15.0
```

This would apply the two recipe parameters to the NGC 253 target when processed by REDUCE_SCIENCE_BROADLINE, while

```
[REDUCE_SCIENCE_BROADLINE:ARP*]
REBIN = 10.0,20.0,30.0
PIXEL_SCALE = 15.0
```

would apply the same parameter values for any beginning with the Arp designation.

6.2.2 Setting recipe parameters by ORAC-DR internal header

The pipeline translates a selection of metadata from the FITS headers into ORAC-DR internal headers. You can choose different sets of recipe parameters from the internal headers. The available headers can be inspected with translatehdr supplied with one of your raw data files.

```
% $STARLINK_DIR/Perl/bin/translatehdr a20151213_00067_01_0001.sdf
```

Here is an example of how to select by internal header.

```
[REDUCE_SCIENCE_NARROWLINE#SAMPLE_MODE=GRID]
LV_IMAGE = 1
LV_AXIS = skylon
```

would apply these parameters only to data whose sample mode was grid.

You can select by an arbitrary number of internal headers to narrow the selection. The internal headers must follow any object name as in the following example.

```
[REDUCE_SCIENCE_NARROWLINE:HH21#SPECIES=C-18-O#BANDWIDTH_MODE=250MHzx4096]
FINAL_LOWER_VELOCITY = -100
FINAL_UPPER_VELOCITY = 100
MOMENTS_LOWER_VELOCITY = 1.2
MOMENTS_UPPER_VELOCITY = 6
FLATFIELD = 0
```

SPECIES defines the molecule. The rationale for this might be disable estimation of the flat field because the signal is much weaker for the molecule C\textsuperscript{18}O. Other common values are C\textsuperscript{0} for \textsuperscript{12}CO and \textsuperscript{13}-C\textsuperscript{0} for \textsuperscript{13}CO. There is also a TRANSITION header to select by the transition.

The velocity limits for the moments might be set narrower than for other molecules. You might want to set a different velocity range in the final spectral cubes (set by the FINAL_LOWER_VELOCITY and FINAL_UPPER_VELOCITY parameters) depending on the spectral resolution given by BANDWIDTH_MODE (see Figure 3.2.3 for a list).
6.3 Setting quality-assurance parameters (optional)

There is a set of quality-assurance (QA) parameters that are applied by default when you run the pipeline. These are found in the text file $ORAC_DATA_CAL/qa.ini.

You can set your own QA parameters by creating a local .ini file (called myqa.ini in the following examples). You can then call this local QA file via -calib qaparams=myqa.ini when starting the pipeline.

The example below illustrates the format of this QA file and highlights some of the main parameters you may consider tweaking.

```
[default]
BADPIX_MAP=0.1
GOODRECEP=8
TSYSBAD=550
FLAGTSYSBAD=0.5
TSYSMAX=550
TSYSVAR=1.0
RMSVAR_RCP=0.5
```

The text in the square brackets describes the data to which the QA parameters should be applied. This is followed by the QA parameters and their values.

The parameters listed under the [default] header will get picked up for all observations unless overridden by other header descriptions. Extra header may describe a frequency range (e.g. [default 200:300]), a particular molecule and transition (e.g. [default C032]), an instrument (e.g. [RXA]), or a legacy survey (e.g. [GBS]). You can also include combinations (e.g. [GBS_13C032]). Note that for any data taken by RxA or RxW, GOODRECEP must be set to 1.

The example file below sets up a different set of parameters for two transitions of CO. Any QA parameters not explicitly set will revert to those specified in the default qa.ini file.

```
[C18O32]
RES_CHAN=10
VELRES=1.0
TSYSBAD=650

[CO21]
RES_CHAN=10
VELRES=0.5
TSYSBAD=550
GOODRECEP=1
```

See Appendix H for a description of all available QA parameters.

6.4 Specifying bad receptors (recommended)

If certain receptors are known to be bad for the full length of an observations (e.g. dead receptors), processing time can be reduced by not having the pipeline attempt to reduce that data.

Information regarding bad receptors is stored in a master text file called index.bad_receptors, located in your $ORAC_DATA_CAL directory. This file lists dates and the corresponding receptors which are not
operational. By default, when the pipeline runs it searches this file and discards the appropriate receptors. However, this master list is grossly incomplete so you should select another method for specifying bad receptors.

We recommend using the index option, called via `-calib bad_receptors=index` when starting the pipeline. This creates an index file called `index.bad_receptors_qa` in your ORAC_DATA_OUT directory, where any bad receptors identified during your reductions are indexed. This file is appended each time you run the pipeline and in this way you build up your own independent list.

If an index file exists, then, by default, the pipeline will look for bad-receptor information in both `$ORAC_DATA_CAL/index.bad_receptors` and `$ORAC_DATA_OUT/index.bad_receptors_qa`.

<table>
<thead>
<tr>
<th>bad_receptors</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>masterorindex</td>
<td>Use both the master <code>index.bad_receptors</code> and pipeline-generated <code>index.bad_receptors_qa</code> files [Default].</td>
</tr>
<tr>
<td>master</td>
<td>Use the master <code>index.bad_receptors</code> file in <code>$ORAC_DATA_CAL</code>.</td>
</tr>
<tr>
<td>index</td>
<td>Use the <code>index.bad_receptors_qa</code> index file in <code>$ORAC_DATA_OUT</code> as generated by the pipeline.</td>
</tr>
<tr>
<td>file</td>
<td>Reads a file called <code>bad_receptors.lis</code>, which should contain a space-separated list of receptor names in the first line. This file must be located in <code>$ORAC_DATA_OUT</code> and invoked by <code>-calib bad_receptors=file</code>.</td>
</tr>
<tr>
<td>list</td>
<td>A colon-separated list of receptor names can be supplied, such as <code>-calib bad_receptors=H01:H06</code>. You can append any of the other options to the end of your list, such as <code>-calib bad_receptors=H14:index</code>.</td>
</tr>
</tbody>
</table>

Table 6.1: The options available for the `-calib bad_receptors` flag when running the pipeline.

### 6.5 Starting the pipeline

1. Initialise the pipeline software. This may be as simple as

   ```
   % oracdr_acsis
   ```

2. Define environment variables to ensure the data is read from, and written to, the right place. Many are set automatically when the pipeline is initialised but others must be set manually. Details of the optional variables are given in [SUN/260](#) but you should specify where to find the raw data and where to write any files that are created.

   ```
   % setenv ORAC_DATA_IN <path to raw data>
   % setenv ORAC_DATA_OUT <where you want reduced data to go>
   ```

   These extra definitions can be avoided if you initialise with the following command.

   ```
   % oracdr_acsis -cwd
   ```

The `cwd` option requests that the current working directory is used for all input and output, which is most likely what you require.

If you are supplying a text file listing the raw data `$ORAC_DATA_IN` should be the location of this file. If supplying an external configuration file it should also be in this location.

If you wish to keep the intermediate files produced by the pipeline you should also set `ORAC_KEEP`. 
% setenv ORAC_KEEP 1

However, this still excludes temporary files made during a recipe step, whose names have the oractemp prefix. To retain these set

% setenv ORAC_KEEP temp

Retention of temporary and intermediate will require plenty of storage, but it can be invaluable during debugging.

(3) Now you are ready to run the pipeline. In this example, the recipe name on the end ensures that all data being processed using REDUCE_SCIENCE_NARROWLINE.

% oracdr -files list.txt -loop file -batch -log xf -calib qaparams=myqa.ini \  
  bad_receptors=index -recpars mypar.ini -nodisplay REDUCE_SCIENCE_NARROWLINE

Below is a list of commonly used command line options when running the ORAC-DR pipeline from outside the EAO. For a full list of all possible options and their descriptions see SUN/230.

<table>
<thead>
<tr>
<th>Flag</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supplying data</td>
<td></td>
</tr>
<tr>
<td>-file &lt;mylist&gt;</td>
<td>Input data provided by a text file. Supply the file name (relative to current directory, or the full path) of an ASCII text file containing a list of all observation files to be reduced, one file per line.</td>
</tr>
<tr>
<td>Looping</td>
<td></td>
</tr>
<tr>
<td>-loop file</td>
<td>Loop over all the lines in the file supplied by the -file option.</td>
</tr>
<tr>
<td>Group processing</td>
<td></td>
</tr>
<tr>
<td>-batch</td>
<td>Delays group processing until the individual files have been reduced.</td>
</tr>
<tr>
<td>-onegroup</td>
<td>Forces all the observations into the same group. Useful if building up a map from rasters with different target co-ordinates or from different dates.</td>
</tr>
<tr>
<td>Supplying parameter files</td>
<td></td>
</tr>
<tr>
<td>-calib</td>
<td>Under the calibration flag you can specify QA parameters by including qaparams=myqa.ini&gt; and bad receptors via bad_receptors=index. If you do not set the qaparams option but have a file called qa.ini in your output directory, the QA settings will come from this file.</td>
</tr>
<tr>
<td>-recpars</td>
<td>Allows you to provide recipe parameters as a .ini file.</td>
</tr>
<tr>
<td>Logs/Display</td>
<td></td>
</tr>
<tr>
<td>-nodisplay</td>
<td>Shorten processing times by turning off all graphical output.</td>
</tr>
<tr>
<td>-log sxfh</td>
<td>Send the log to a screen (s), an xwindow (x), file (f) or html (h). The logfile (f) has the name .oracdr_NNNN.log where NNNN is the current process ID. Only include the options you want. This defaults to xf.</td>
</tr>
</tbody>
</table>

Table 6.2: The options available on the command line when running the ORAC-DR pipeline from outside the EAO.
6.6 Pipeline output

The pipeline will produce a group file for each object being processed. If the pipeline is given data from multiple nights, all those data will be included in the group co-add using inverse variance weighting.

Files created from individual observations are prefixed with a, while group (co-added) maps are prefixed with ga. Table 6.3 describes the files created. In addition PNG images are made of the reduced files at a variety of resolutions.

**Tip**

TIP: Even if just a single observation is processed, a group file is created so long as the observation passes the QA check.

6.6.1 Why have multiple reduced files been generated?

You will find the pipeline splits large reduced cubes (e.g. from raster maps) into smaller tiles of <512 MB. This is to save on computer memory. It does this from the central position outwards so you may find some of the smaller edge tiles are strange, often narrow, rectangles. These tiles can be pasted together with the KAPPA command `paste` but beware of the final file size. For example,

```
% paste ga20140601_15_1_reduced/*.sdf tiledmap
```

Note, there is a recipe parameter CHUNKSIZE which adjusts the maximum tile size. If you make it larger than 512 it is possible to generate a single reduced cube.

In addition to these NDFs a number of log files are created.

Finally there are HDS scratch `t*.sdf` files, and temporary files `oractemp*` which can be NDFs or small text files such as file lists. These should be removed automatically at the end of processing, unless something has gone wrong.
### Default Files

<table>
<thead>
<tr>
<th>Default Files</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>cube001</td>
<td>Baselined cube</td>
</tr>
<tr>
<td>integ</td>
<td>Integrated intensity image</td>
</tr>
<tr>
<td>rimg</td>
<td>Representative image (same as integ file), used to form rimg PNG</td>
</tr>
<tr>
<td>sp001</td>
<td>Spectrum taken from position of peak intensity in the integ file</td>
</tr>
<tr>
<td>rsp</td>
<td>Representative spectrum (same as sp001), used to form rsp PNG</td>
</tr>
<tr>
<td>iwc</td>
<td>Intensity weighted co-ordinate image</td>
</tr>
<tr>
<td>noise</td>
<td>Noise map</td>
</tr>
<tr>
<td>reduced00n</td>
<td>Final trimmed, baselined cube of the $n^{th}$ tile. There may be a few of these as large maps will be split into tiles of 512 MB.</td>
</tr>
<tr>
<td>rmslo</td>
<td>Low-frequency noise</td>
</tr>
<tr>
<td>rmshi</td>
<td>High-frequency noise</td>
</tr>
</tbody>
</table>

### Extra files kept with ORAC_KEEP = 1

<table>
<thead>
<tr>
<th>Extra files kept with ORAC_KEEP = 1</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>em001</td>
<td>Ends of the frequency axis have been trimmed off</td>
</tr>
<tr>
<td>thr001</td>
<td>Time-series data with large spikes removed</td>
</tr>
<tr>
<td>ts001</td>
<td>Time-sorted time-series data</td>
</tr>
<tr>
<td>tss001</td>
<td>Time-series data with median DC signal removed</td>
</tr>
<tr>
<td>blmask001</td>
<td>Baseline mask cube. Regions of emission have been masked out.</td>
</tr>
<tr>
<td>b1001</td>
<td>Baselined cube</td>
</tr>
<tr>
<td>linteg00n</td>
<td>Integrated intensity image formed around the $n^{th}$ line.</td>
</tr>
</tbody>
</table>

Table 6.3: Table of the files written out by the science pipeline. Each of these files is generated for both the individual observations and the group files.

### Default Files

<table>
<thead>
<tr>
<th>Default Files</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>.oracdr_<em>.</em>.log</td>
<td>The ORAC-DR log file.</td>
</tr>
<tr>
<td>log.flat</td>
<td>Flat-field ratios for each receptor and observation.</td>
</tr>
<tr>
<td>log.group</td>
<td>The files contributing to each group.</td>
</tr>
<tr>
<td>log.noisestats</td>
<td>Noise statistics for each observation and group.</td>
</tr>
<tr>
<td>log.qa</td>
<td>Quality assurance reports</td>
</tr>
<tr>
<td>log.removedobs</td>
<td>Observations removed from each group (e.g. due to failing QA).</td>
</tr>
</tbody>
</table>

Table 6.4: Table of the log files written by the science pipeline.
Chapter 7
Regridding your Data

If you prefer to reduce your data manually, regridding your data is the best place to start. (See Appendix D for an explanation of what regridding is.)

To convert your raw time-series cubes with spectral channel number, receptor index, time-slices axes into a spatial cube with RA, Dec (or Galactic longitude, Galactic latitude) and spectral axes use the SMURF application `makecube`. In this chapter we will show an example of processing data using `makecube`, discuss what to look out for and introduce the various parameters with which to tailor your reduction.

7.1 Running Makecube

The SMURF application used for regridding your raw data is `makecube`.

```bash
% makecube in=a20070505_00041_01_0001.sdf out=cube autogrid
```

Processing data from instrument 'HARP' for object 'W49' from the following observation:

```
20070505 #41 grid/pssw
```

Projection parameters used:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRPIX1</td>
<td>0</td>
</tr>
<tr>
<td>CRPIX2</td>
<td>0</td>
</tr>
<tr>
<td>CRVAL1</td>
<td>287.555875 ( RA = 19:10:13.410 )</td>
</tr>
<tr>
<td>CRVAL2</td>
<td>9.10386111111111 ( Dec = 9:06:13.90 )</td>
</tr>
<tr>
<td>CDELT1</td>
<td>-0.00166666666666667 ( -6 arcsec )</td>
</tr>
<tr>
<td>CDELT2</td>
<td>0.00166666666666667 ( 6 arcsec )</td>
</tr>
<tr>
<td>CROTA2</td>
<td>0</td>
</tr>
</tbody>
</table>

Output cube pixel bounds: (-8:11, -8:11, -1024:1023)

Output cube WCS bounds:

- Radio velocity (LSB): -443.8134 -> 464.2568 km/s

The autogrid option allows the software to determine the optimal projection parameters for regridding. This is usually fine for stares and jiggles but is not so good for raster maps. See Section 7.2.5 for more discussion.

The screen report generated by `makecube` includes the input files, instrument, source, UT date and observation number, and observing mode. The pixel size can be checked in the projection parameters section, while the bounding box of the resulting cube (RA, Dec and velocity) is reported in the output section.

You can visualise your map by opening it with GAIA—see Figure 7.1.
Figure 7.1: The regridded cube displayed with GAIA. The 5×5 jiggle pattern is evident in the map as is the missing receptor in the top-left corner. The smaller window shows the spectrum for the pixel selected by the blue cross on the map.

### 7.1.1 Reducing multiple observations

You can supply `makecube` a group in a text file containing a list of all the raw files you want reduced. These filenames should include the full path if they are not in the local directory.

When you pass such group files to `makecube` (and any Starlink command) you should prefix the filename with an up-caret (`^`).

```
% makecube in=^filelist.txt
```

Alternatively you can use wild cards. The example below reads in all the raw files for observation 10.

```
% makecube in=rawdata/a20140101_00010\*
```
7.2 Makecube Options

7.2.1 Specifying spectral bounds

To save disk space and processing time you can specify the region of the spectra to be processed with `SPECBOUNDS`. If you know your line lies close to 0 km s\(^{-1}\), you may choose to process only the central 100 km s\(^{-1}\) as in the example below.

```
% makecube rawfile specbounds="-50.0 50.0"
```

7.2.2 Masking receptors

When combining several maps with masked bad receptors one can use the `BADMASK` parameter of `makecube`. This option determines the way in which bad pixels are propagated from input to output. The one that produces the best map is `badmask=and`, which uses all the data so an output pixel will be bad only if all the input pixels that contribute to it are bad. This generates an output map with the lowest noise and fewest bad pixels. However, for large datasets the memory requirements may be excessive.

Other options are `badmask=or` (default) and `badmask=first`. `Or` means that an output pixel will be bad if any of the input pixels that contribute to it are bad and is the default. The flag `first` means that the decisions on which pixels will be flagged as bad will be made with the first input spectrum while the rest are ignored.

7.2.3 Including/excluding receptors

To make a cube with only certain receptors you can use the `detectors` option on the command line. This allows you to either include or exclude specific receptors without the need for masking. The example below makes a map using all receptors except H04 and H11.

```
% makecube in=rawfile autogrid out=map detectors='"-H04,H11"
```

This alternative example makes a map using only receptor H10. Maps made with single receptors may be used to evaluate the receptor-to-receptor flat-field.

```
% makecube in=rawfile autogrid out=map detectors='"H10"
```

7.2.4 Defining an output grid

You can use the `REF` option to define an NDF which is used to define an output grid. This NDF can even be in two dimensions even though your data may be in three dimensions.

```
% makecube in=rawfile ref=myreffile
```

If you do not supply a reference file `makecube` will revert to the `AUTOGRID` option.

If `autogrid=true`, the output grid is determined automatically so that as many data samples as possible fall close to the centre of pixels in the output cube.

If `autogrid=false`, `REFLON` and `REFLAT` are set to the first pointing BASE position, `CR\_TA\_2` is set to the `MAP_PA` value in the FITS header (converted to the requested sky co-ordinate system), `PIX\_SIZE` is set to 6 arcseconds, and `REPM\_X1` and `REPM\_X2` are both set to zero. See `SUN\_258` for a full description of each of these parameters.
7.2.5 Data regridding options

There are several regridding options available to you through the `makecube` command. These are specified with the `SPREAD` parameter on the command line. For instance,

```
% makecube in=rawfile spread=sincsinc params="[6,9]"
```

The default method is `Nearest`, which assigns the input pixel completely to the nearest output pixel. This is the fastest method available but is not optimal. In particular it may result in blank pixels in HARP maps due to missing receptors (see Figure 7.2).

We recommend you select one of the other methods available which spread the emission to neighbouring pixels. These include `Gauss` and `SincSinc` which are the most common, although the latter sometimes gives noisy edges with negative values in some pixels. `SincCos` will give neater edges. For each of these you will need to provide the size of the convolution function through the `params` option as in the example above. See [SUN/258] for more details.

Figure 7.2: Raster map regridded with `makecube` and `spread = nearest` (left), `Gauss` (centre) and `SincSinc` (right). Blank pixels are coloured blue. You can see the Nearest option has resulted in multiple blank pixels throughout the map.

7.2.6 Generating a variance map

The option `GENVAR` can be used to generate a variance array for your cube. This is important if you are adding multiple maps with different variances as it allows them to be accurately weighted. There are three options for `GENVAR`:

**Spread**  
The output variance values are based on the spread of input data values contributing to each output pixel. Note that this option is not available if parameter `SPARSE` is set `true`. If the `BADMASK` value is `or` or `first`, then a single variance value will be produced for each output spectrum. However, when `BADMASK` is `and`, an independent variance value is calculated for each channel in each output spectrum.

**Tsys**  
The output variance values are based on the system noise temperature values supplied in the input NDFs. Since each input spectrum is characterised by a single `Tsys` value, each output spectrum will have a constant variance value (i.e. all channels in an output spectrum will have the same variance value). [Default].

**None**  
No output variance values are created.
7.2.7 Sparse grid

If one has observed a number of offset positions which are not on a regular grid or are widely spaced, it is of little use to make a normal cube with `makecube`, which then would have a large size and which would be mostly empty. Then one can use the `makecube` parameter `SPARSE`. When `sparse=true` a one-dimensional array is created which stacks spectra in the order in which they were observed (from left to right when viewed with GAIA).

```
% smurfhelp makecube param sparse
```

This is generates a one-dimensional array where spectra are displayed by GAIA in the order where they were observed (from left to right).

7.2.8 Creating a catalogue of receptor positions

You can use the option `OUTCAT` to generate a catalogue of the spatial positions of the receptors used to make your final cube. The label associated with each row in the catalogue is the detector name. The detector positions in the catalogue are ordered as follows: all the positions for the first input NDF come first, followed by those for the second input NDF, etc. Within the group of positions associated with a single input NDF, the positions for the first time slice come first, followed by the positions for the second time slice, and so on.

```
% makecube in=rawfiles outcat=cat
```

The catalogue produced will be in FITS format. In the example above a file called `cat.FIT` is created. When viewing your map with GAIA this catalogue can be overlaid to identify the receptors contributing to each pixel (see Figure 7.3).

![Figure 7.3: The receptor positions overlaid on a regridded cube of a HARP stare observation. This is viewed in GAIA by selecting Data-Servers > Local Catalogs and selecting your OUTCAT filename (here cat.FITS). Notice that dead receptors are excluded from the list.](image-url)
7.2.9 Tile dimensions

For large data sets, it may be beneficial to break the output array up into a number of smaller rectangular tiles. This can be controlled by the TILEDIMS parameter. The files can be stitched together later using the KAPPA application paste which may be used any time the tiles to be abutted have the same pixel co-ordinates. Each tile may also have a rim of extra data to allow for future co-adding, the width of which is set by the TILEBORDER parameter.
Chapter 8
Analysing your Cube

8.1 Smoothing your data

Frequency or velocity smoothing is performed using \texttt{KAPPA block}. It uses a rectangular box filter with each output pixel either the mean or the median of the input pixels within the filter box. The box size can be set to 1 for dimensions which do not require smoothing. In the example below the spatial pixels remain untouched while the velocity axis is smoothed using a box of five channels.

\begin{verbatim}
% block in=mycube out=rebinnedcube box="[1,1,5]"
\end{verbatim}

Two-dimensional NDFs can also be smoothed using \texttt{gaussmooth}. This smooths using a symmetrical Gaussian point spread function (PSF) of specified width(s) and orientation. Each output pixel is the PSF-weighted mean of the input pixels within the filter box.

\begin{verbatim}
% gaussmooth in=mymap out=smoothedmap fwhm=3
\end{verbatim}

Note that the \texttt{fwhm} option is given in the number of pixels. For example, to smooth a map with 4″ pixels by a 12″ Gaussian you would set \texttt{fwhm=3}.

8.2 Removing a baseline

Baselines can be removed using \texttt{KAPPA mfittrend}. This routine can fit polynomials up to order 15, or cubic splines, to each spectrum in your cube. You can specify the ranges to fit via the \texttt{ranges} parameter, or you can allow them to be determined automatically (\texttt{auto}), say if the number of observations is large.

\begin{verbatim}
% mfittrend in=cube ranges="-50 -10 80 160" order=1 axis=3 out=baselinedcube
\end{verbatim}

If using automatic range determination you should set the \texttt{numbin} option. This is the number of bins in which to compress the trend line. A single line or average may be noisy so binning is used to improve the signal-to-noise in order to enhance features that should be masked.

Ideally the bin size should match your line width to get maximum single to noise between the emission and the background. Be aware that bins that are too big can dilute weaker features. Likewise, bins that are too small will get noisy at the edges of broad lines. We recommend you experiment with the bin size to find the best fit for your data.

To exclude features that are not part of the baseline trend you can use the \texttt{clip} option. Use \texttt{clip} to provide an array of standard deviations for progressive clipping of outliers within each bin. Once the data have been binned a trend is fit within each bin and the outliers clipped, the trend is then re-fitted and the outliers again clipped etc. By default this will clip at 2, 2.5 and 3\(\sigma\) successively but you may wish to experiment with your own clip levels. The \texttt{clip} option is only used when \texttt{auto=true}.

For convenience \texttt{GAIA} has a \textbf{Baseline} tab in its cube control panel—see Section 10.1 for an example. This invokes \texttt{mfittrend}. 

8.2.1 Advanced method

These steps give a more in depth way of determining the baselines and mimic the pipeline.

1. Perform a block smooth on your reduced cube. Here the smoothing is quite aggressive with a box filter of five pixels along the spatial axes and fifteen pixels along the frequency axis. This is to really pull out all emission features. You can tweak these to suit your data, e.g. a narrower box might be needed if you have very narrow lines.

   \[
   \text{% block in=cube out=temp1 box=[5,5,15] estimator=mean}
   \]

2. Perform mfittrend on your smoothed cube with a high-order polynomial and automatic range determination.

   \[
   \text{% mfittrend in=temp1 out=temp2 axis=3 order=3 auto method=single \ variance subtract=false mask=blmask}
   \]

3. Add the baseline mask to your original unsmoothed cube.

   \[
   \text{% add in1=cube in2=blmask out=temp3}
   \]

4. Perform mfittrend on your masked unsmoothed cube with a lower-order polynomial. This time fit the full range by setting auto=false.

   \[
   \text{% mfittrend in=temp3 out=temp4 axis=3 order=1 auto=false ranges=\! \ method=single variance=true subtract=false}
   \]

5. Subtract the baseline from the original unsmoothed cube.

   \[
   \text{% sub in1=cube in2=temp4 out=baselinedcube}
   \]

8.2.2 What about findback?

The CUPID routine findback offers an alternative for background subtraction however there are more limitations. It applies spatial filtering to remove structure with a size scale less than a specified box size. Within each box the values are replaced by the minimum of the input values. The data are then filtered again and this time replaced with the maximum in each box.

Using findback results in a baseline trend that hugs the lower limit of the noise and can contain sharp edges. These problems can be mitigated but extra steps are required. See SUN/255 for more details.

8.3 Collapsing your map

An integrated intensity map can be created by collapsing your cube along the frequency/velocity axis using KAPPA collapse. For each output pixel, all input pixels between the specified bounds are collapsed and combined using one of a selection of estimators. Amongst others, the estimators include the mean, integrated value, maximum value, the mean weighted by the variance, RMS value and total value. See SUN/95 for a full list.

The example below includes the options low and high which can be specified to limit the range over which the cube is collapsed on the given axis (in this case from $-5$ km s$^{-1}$ to $+10$ km s$^{-1}$). The variance flag indicates the variance array should be used to define weights and generate an output variance. The option wlim sets the fraction of pixels that must be ‘good’ in the collapse range for a valid output pixel to be generated. You may find you need to reduce the value for wlim below its default of 0.3 for some data.
% collapse in=cube axis=vrad estimator=integ variance=true low=-5.0 high=10.0 \ wlim=0.5 out=integmap

If you do not know the axis name you can give the number instead (1=RA, 2=Dec, 3=vrad).

For convenience GAIA has a Collapse tab in its cube control panel—see Section 10.6 for an example. This invokes collapse.

8.3.1 Advanced method

These steps mimic the pipeline and show the procedure for generating an integrated map collapsed only over regions with emission greater than 3\(\sigma\).

1. Use findclumps to run a clump-finding algorithm on your cube. Specify the 3\(\sigma\) limit in your configuration file. See Section 9.5 for more details on clump-finding and Section 8.9 for how to determine your RMS.

% findclumps in=cube rms=<medianrms> config="myconfig.dat" \ method=clumpfind out=temp1 outcat=mycat deconv=no

2. Divide the map by itself to create a clump mask that has clump regions set to 1.

% div in1=temp1 in2=temp1 out=temp2

3. Set the bad data to zero using KAPPA nomagic.

% nomagic in=temp2 out=temp3 repval=0

4. Multiply your reduced cube by the clump mask.

% mult in1=cube in2=temp3 out=maskedcube

5. Collapse your masked reduced cube.

% collapse in=maskedcube out=integ estimator=integ wlim=0.1 variance

8.3.2 Moments Maps

You can use collapse to generate the moments maps by selecting the appropriate estimator option—Integrated value (Integ) for the integrated map (zeroth moment), Intensity-weighted co-ordinate (Iwc) to get the velocity field (first moment), or Intensity-weighted dispersion (Iwd) to get the velocity dispersion (second moment).

Tip

TIP: You can also use the PICARD recipe CREATE_MOMENTS_MAPS. See Appendix A for details. This recipe follows the advanced method outlined above.
8.4 Temperature scales

Your cube will come out of `makecube` and the pipeline, in units of $T_A^*$. To convert this to main-beam brightness temperature, $T_{MB}$, divide your cube by the main-beam efficiency, $\eta_{MB}$. Alternatively, to convert to receiver temperature, $T_R^*$, divide by the forward scattering and spillover efficiency, $\eta_{fss}$. See Section 3.2 for efficiency values for RxA and HARP, and the JCMT webpages for further information and historical numbers.

You can use the KAPPA command `cdiv` to divide any NDF by a constant.

```%
% cdiv in=harpcube scalar=0.63 out=harpcube_Tmb
```

8.5 Changing the pixel size

You may want to `regrid` your data onto larger pixels, for instance to allow direct comparison with data from other observatories. In the example below a JCMT map is regridded and aligned to match a Herschel map. See Appendix B for instructions on converting your FITS file to NDF format.

```%
% wcsalign in=jcmtmap out=regridmap lbnd=! ubnd=! ref=herschelmap rebin conserve=f
```

Alternatively, to `resample` your data onto smaller pixels you should use the KAPPA command `sqorst`. In the example below 'map' has a pixel size of 8″, while 'resamplemap' has a pixel size of 4″ – the number of pixels has been doubled by applying a factor of 2 to the spatial axes. A factor of 1 was applied to the frequency (third) axis leaving it unchanged.

```%
% sqorst in=map out=resamplemap factors="[2,2,1]" conserve
```

`mode=factors` is the default setting so it was not specified in the example above. The example below however, uses `mode=pixelscale` to define a pixel size for the third axis; here the spectra are rebinned into 2 km s$^{-1}$ channels.

```%
% sqorst in=map out=resamplemap mode=pixelscale pixscale=2 axis=3
```

Remember you can check your current pixel size and channel spacing with `ndftrace` (see Section 2.4).

8.6 Mosaicking cubes

If you pass raw files covering different regions of the sky to `makecube` it will automatically mosaic them together. This can be heavy work for your processor so you may wish to make individual cubes and combine them during post-processing. To co-add multiple reduced maps you should use `wcsmosaic`.

Note that this is not the same as stitching the tiles of a reduced cube from a single `makecube` command. Such tiles share common pixel co-ordinates and so can be combined with `paste` (Section 6.6.1). Separately created cubes will not have the same pixel co-ordinates, and therefore the world co-ordinates are required to align the tesserae in the mosaic of an extended region.

```%
% wcsmosaic in=^maplist out=mosaic lbnd=! ubnd=! variance
```
By selecting the lower bound (lbnd) and upper bound (ubnd) to be default (!) you are including all of the input tiles. You can change these if you want to only mosaic a sub-region of the input maps. As with makecube there are a number of regridding options available to you describing how to divide an input pixel between a group of neighbouring output ones (the default is SincSinc).

Note that by default wcsmosaic aligns reduced cubes along the spectral axis using the heliocentric standard of rest (the ORAC-DR pipeline also does this). If you want to align using a non-heliocentric standard of rest, you should set the AlignStdOfRest attribute for your NDFs using wcsattrib before running wcsmosaic. The following example sets the alignment to the kinematic LSR.

```
% wcsattrib <list_of_separate_cubes> set AlignStdOfRest LSRK
```

where <list_of_separate_cubes> is group of cubes specified as a comma-separated list or as one per line in a text file.

**Tip**

Take care not to combine data separated on the sky as wcsmosaic will attempt to create a vast cube that encompasses all the input files until it runs out of resources.

**Tip**

You can also use the Picard recipe MOSAIC_JCMT_IMAGES. This will correctly combine all NDF extensions. See Appendix A for details.
8.7 Cropping your map

Cropping an ACSIS map can be fiddly. The simplest way is to create an ARD mask in GAIA and apply it to your map. The steps below work on both two- and three-dimensional data.

1. Create your ARD mask. You may find it easiest to do this with GAIA. See Figure 8.2 for an illustrated guide.
   
2. Trim off the third axis from your mask using `ndfcopy`.
   
   ```
   % ndfcopy mask trim trimwcs
   ```

3. Apply the saved ARD mask to your map. Setting `inside=false` will mask the pixels outside rather than inside your mask. The masked pixels will appear blank when you open it with GAIA; see the left-hand panel of Figure 8.2.
   
   ```
   % ardmask map inside=false ard=ardmask.txt out=maskmap
   ```

4. Trim off the blank pixels using `ndfcopy` with the `trimbad` option. This leaves just your selected region; see the right-hand panel of Figure 8.2.
   
   ```
   % ndfcopy maskmap trimbad
   ```

An alternative method is to use `ndfcopy` while defining the section of the map or cube you wish to extract as an output cube. See Section 2.6.

8.7.1 Supplying a template

If you wish to extract only a region which overlaps with an existing file you have, e.g. from a different observing campaign or telescope, you can also use `ndfcopy` but with the `like` option.

   ```
   % ndfcopy in_full out_cropped like=map2 likewcs
   ```

The shape of the file supplied by `like` will determine the shape of the output file. This shape can be in either pixel indices or the current WCS Frame. If the WCS Frame is required, include the parameter `likewcs` to the command line otherwise it can be omitted.
Defining an ARD region in GAIA

Open your map with % gaia map

In GAIA go to Image-analysis>Image regions.

Select the shape of the ARD region you wish to define and drag it on your map by holding the mouse button down, dragging the shape out, then releasing the button.

In the “Image regions” window go to File>Save ARD description to save your ARD mask for later use.

Figure 8.1: Defining an ARD region using GAIA
8.8 Filling holes in your map

You may come across empty pixels in your map due to dead receptors or receptors which have failed quality assurance in the pipeline. The second half of 2013 in particular had only twelve working receptors for HARP.

You can fill these holes using \texttt{fillbad}. This replaces the bad values with a smooth function derived from neighbouring values, derived by iterating to a solution of Laplace’s equation.

The default values for \texttt{fillbad} will fill the holes but smooths by five pixels along each axis. If you prefer not to smooth in the spectral axis, set the parameter \texttt{size} to \( [s,s,0] \) where \( s \) is the scale length in pixels. The zero means do not smooth along the third axis.

The scale length should have a value about half the size of the largest region of bad data to be replaced. Since the largest bad regions apart from the cube peripheries are two pixels across, a size of 1 is appropriate.

\[
\% \text{ fillbad in=holeymap out=filledmap size=[1,1,0]} \]

Figure 8.3 shows an initial map with holes and the final filled map.

8.9 Checking the noise

You can use \texttt{stats} to check the noise in your map. It will report the statistics for all pixels so be aware that noisy edges and strong signal will contribute to the standard deviation. You can mitigate this by trimming any noisy edges and by examining the square root of the VARIANCE component (hereafter referred to as the error component) although bright emission will still increase your noise. You can select the error component with \texttt{comp=err} on the command line.

\footnote{No such component exists in the NDF.}
Figure 8.3: Filling holes in your HARP map with `fillbad`. Compare the original map (left) with the filled map (right). A blue pixel indicates an undefined spectrum.

```
% stats file comp=err order
```

Including the option `order` allows the ordered statistics such as the median and percentiles to be reported. Note that percentile options will need to be specified via the `percentiles` parameter.

**Tip**

Remember the mean or median values will give you the noise when using the error component.

### 8.9.1 Visualising the noise

You can plot the noise or error component of your map using the KAPPA command `histogram`. This allows you to visualise the distribution with more ease. Again the `comp=err` option is used.

```
% histogram mosaic comp=err range=! numbin=200
```

The output is shown in Figure 8.4. An alternative to setting the number of bins via the `numbin` parameter is to set the width of each bin using the `width` parameter.

It is also useful to view the noise map itself. Figure 8.5 shows how to select the error component in GAIA. Other options available from the "Select NDF in container file" window include the exposure time, the effective time and, if `spread=nearest` when running `makecube`, the system temperature. To return to your main image select the top level and click the Data button.

### 8.9.2 HARP Flatfielding

The individual detectors in the HARP array do not respond exactly the same to the incoming signal, returning different temperatures for the same flux. If uncorrected, this can lead to artificial net-like
Tip

TIP: You can write out the error component into a new file using `ndfcopy`.

```
% ndfcopy map comp=err noisemap
```

patterns in the reduced spectral cube. As with any flatfield correction, the goal is to expose to a uniform source to measure the relative responses of the detectors. However, this is not possible with HARP.
observations, and the approach is assume that during an observation the detectors see approximately the same signal from the various sources. For extended emission at low galactic latitudes this is a reasonable assumption. For isolated compact sources it is likely to be invalid.

It may be possible to use a flatfield determined on the same night in a high-signal region and apply that to a low-signal or compact-source observation. The flatfield can change during the night, but it might better than no flatfield.

The method of Curtis et al. (2010) creates a map for each detector and integrates the measured flux in the main spectral line. Use the DETECTORS parameter to create a spectral cube from just that detector.

```
% makecube in=rawfile out=cube_H01 detectors="'H01'" autogrid
```

The simplest way to sum the flux across a line run stats over a chosen spectral range, such as $-5 \text{ km s}^{-1}$ to $7.2 \text{ km s}^{-1}$.

```
% stats cube_H01"(,,,-5.0:7.2)"
```

If there might be bad pixels present, the mean is more accurate than the sum. This assumes that the line is located within these bounds across the whole spatial region. It is wise not to push too far into the wings of the line and baseline errors and noise have a greater impact on the integrated flux.

The receptors are normalised to the flux of the reference receptor, near the centre, normally H05, but given by the FITS header REFRECEP.

There are other methods in ORAC-DR, one to cope with multiple lines. It sums all the signal above some threshold, such as the median plus four standard deviations, to exclude the baseline noise. Since the flat ratio biases this sum, ORAC-DR iterates to converge to a solution.
Chapter 9
Advanced Analysis

9.1 Changing co-ordinate frames

Co-ordinate systems of regridded Starlink files are described by the world co-ordinate system, (WCS). There are a number of basic co-ordinate systems (or frames) common to all NDFs; these are described by their DOMAIN (essentially their name) and are PIXEL, AXIS, GRID and FRACTION. Additional frames can be stored in the WCS component. Two common additional frames are SKY and SPECTRUM. SKY refers to two-dimensional frames (known as SkyFrames) which describe sky co-ordinates. SPECTRUM refers to one-dimensional frames (known as SpecFrames) that describe a position within a spectrum.

The choice of co-ordinates within the SkyFrame or SpecFrame is called the system. For example, for SkyFrames this may be Galactic or FK5, while for SpecFrames this may be velocity or frequency.

The current frame and the system can both be changed using the KAPPA applications wcsframe and wcsattrib. The current frame for data processed with makecube (either manually or by the pipeline) typically has a DOMAIN of SKY-DSBSPECTRUM. The compound name refers to the first two axes of the frame having sky co-ordinates and the third axis having dual side-band spectral units. You can check this with ndftrace:

```bash
% ndftrace file | grep Domain
```

You can change the attributes of a cube using wcsattrib. To change the SkyFrame co-ordinate system set the System attribute.

```bash
% wcsattrib file set system galactic
```

To change between velocity and frequency you also use the System attribute. For SKY-DSBSPECTRUM the software knows which axis is being referred to based on the option you supply (the third in this case).

```bash
% wcsattrib file set system freq
% wcsattrib file set system vrad
```

Once a cube has been collapsed and is two-dimensional its Frame becomes SKY. If you need to change frames manually use wcsframe.

```bash
% wcsframe file sky
```

For offset co-ordinates you will need to set the system skyrefis to origin. The final two lines in the example below convert the offset units to arcseconds instead of radians.

```bash
% wcsattrib file set skyrefis origin
% wcsattrib file set 'format(1)' 's.*'
% wcsattrib file set 'format(2)' 's.*'
```
### 9.2 Hybrid Data

To merge two hybrid observations run wcsalign on both files.

```
% wcsalign in="rawfile_01.sdf,rawfile_02.sdf" insitu lbnd=! ubnd=! ref=! 
```

Next trim each subsystem to remove noisy ends of the spectra in the overlap region. You can get the pixel bounds from ndftrace (here 1024). The example below trims 35 channels from the ‘left’ of rawfile_01 and 24 channels from the ‘right’ of rawfile_02.

```
% ndfcopy in='rawfile_01(35:1024,,)' out=trimfile_01
% ndfcopy in='rawfile_02(0:1000,,)' out=trimfile_02
```

At this point the subsystems are aligned pixel for pixel. So a subtraction with sub will generate the differences in the trimmed overlap region analysed by stats from which the median is found, which is 0.04 in the example below.

```
% sub trimfile_01 trimfile_02 overlap_12
% stats overlap_12 order
% cadd trimfile_02 0.04 offsetfile_02
```

You can then apply the offset to the second subsystem with cadd. Then the first subsystem can then be merged using wcsmosaic.

```
% wcsmosaic in="rawfile_01,offsetfile_02" out=rawfile12 lbnd=! method=nearest accept
```

You should check the final spectra to make sure there is no noise bump in the middle where they overlap.

Another technique to locate the noisy edges is apply collapse to all the spectra in an observation using the estimator=sigma option then smooth. The composite formed will show a smooth noise profile, increasing dramatically at its end. The trim limits can be estimated manually, or a linear trend fit with mfittrend will return the bounds of the flat low-noise portion of the spectrum in its aranges parameter.

```
% collapse in=rawfile_01 out=profile axis=spec wlim=0.0 estimator=sigma trim
% block in=profile out=profile_sm box=25
% mfittrend in=profile_sm out=junk axis=1 method=region auto order=0
% parget aranges mfittrend
```

In the example above, parget should return just one pair of pixel co-ordinates, which can then form part of an NDF section to extract the non-noisy part of rawfile_01 using ndfcopy. If there is more than one range you want to use the lowest and highest values.

### 9.3 Position-velocity diagram

You can create a position-velocity map by collapsing over the skylat or skylon axis of a reduced cube. Use the KAPPA command collapse with axis=skylat:

```
collapse in=reduced.sdf axis=skylat estimator=sum out=pv 
```

You can view your pv map with GAIA or display.

To obtain a position-velocity map at an arbitrary angle, there is a PVSLICE in the DATAcube package. This can be invoked directly, or its recipe extracted from the PVSLICE script, if you know the co-ordinates of the ends of the slice and do not need the graphics.
9.4 Creating channel maps

The KAPPA application **chanmap** creates a two-dimensional channel map from a cube. It collapses along the nominated axis (with many of the same parameters as **collapse**). The number of channels to create is given by nchan and these are divided evenly between your ranges. The arrangement of the resulting panels is determined by the shape parameter. The collapsed slices are tiled with no margins to form the final image.

```
% chanmap in=cube axis=3 low=-10 high=5 nchan=6 shape=3 estimator=mean
```

This grid of channel maps is filled from left to right, and bottom to top. It can be viewed with **GAIA** (see Figure 9.1) or with **display**.

```
% display chanmap mode=faint noaxes lut=$STARLINK_DIR/bin/kappa/smooth3_lut
```

Channel maps can also be created using **GAIA**. See Section 10.2 for instructions.

![Image of channel map](image)

Figure 9.1: Displaying a channel map with **GAIA**

9.5 Clump finding

The CUPID application **findclumps** can be used to generate a clump catalogue. It identifies clumps of emission in one-, two- or three-dimensional NDFs. You can select from the clump-finding algorithms
FellWalker, GaussClumps, ClumpFind or Reinhold. You must supply a configuration file which lists the options for whichever algorithm you chose (see the CUPID manual for a full list). The result is returned as a catalogue in a text file and as a NDF pixel mask showing the clump boundaries (see Figure 9.2). See Appendix E for descriptions of the various algorithms.

```bash
% findclumps in=map out=clumpmap outcat=clumps.FIT logfile=clumps.log \
  config=myconfig.dat method=clumpfind rms=0.2 shape=polygon
```

The shape option allows findclumps to create a shape that should be used to describe the spatial coverage of each clump in the output catalogue. It can be set to "None", "Polygon" or "Ellipse". The shape - as described in the output catalogue—is in "STC-S" format. STC-S is a textual format developed by the IVOA for describing regions within a WCS—see here for details. The STC-S descriptions are added as extra columns to the output catalogue.

**Figure 9.2**: A velocity slice of the result of three-dimensional clump finding viewed with GAIA. This output NDF contains boundaries of the clumps, with the value reflecting the number of pixels contained within that clump.

**Polygon** Each polygon will have, at most, 15 vertices. For two-dimensional data the polygon is a fit to the clump’s outer boundary (the region containing all good data values). For three-dimensional data the spatial footprint of each clump is determined by rejecting the least significant 10% of spatial pixels, where “significance” is measured by the number of spectral channels that contribute to the spatial pixel. The polygon is then a fit to the outer boundary of the remaining spatial pixels.
**Ellipse**  All data values in the clump are projected onto the spatial plane and “size” of the collapsed clump at four different position angles—all separated by $45^\circ$—is found. The ellipse that generates the same sizes at the four position angles is then found and used as the clump shape.

You can plot the clump outlines over an image using GAIA. See Section 10.4 for instructions.

### 9.6 Using SPLAT to identify telluric emission

Occasionally you may see unexpected emission within your data. An example is shown in Figure 9.3. In this figure, we use the average spectrum feature (see Section 10.5)—and in this example—we see expected bright emission around $7 \text{ km s}^{-1}$. In addition to the expected bright emission, we see some faint emission around $-30 \text{ km s}^{-1}$.

Figure 9.3: An example of a spectrum with bright expected emission around $7 \text{ km s}^{-1}$ and unexpected emission around $-30 \text{ km s}^{-1}$. The data are displayed using GAIA.

We can use SPLAT to investigate this emission further (see Section 10.8 on how to open up a spectrum in SPLAT).

Figure 9.4: Displaying a channel map with SPLAT.
Figure 9.5: Select Observer from the Standard of rest Menu and select Apply.

It is possible to use SPLAT to change the units to Standard of rest: Observer by first going to Analysis and clicking on Change units.

We then use the drop-down menu next to Standard of rest to select Observer from the list, and select Apply.

Figure 9.6: Spectrum from the observer rest frame. We see the unexpected line is found at 0 km s\(^{-1}\), and is likely telluric contamination.

Now we see the unexpected line is at 0 km s\(^{-1}\), and is therefore likely to be contamination from telluric lines.
Chapter 10
Using GAIA

10.1 Removing a baseline with GAIA

(1) Select the spectrum you want to use as your template for the entire cube.

(2) Select the Baseline tab in the "Display image sections of a cube" window.

(3) Select the order of the baseline you want to fit and remove.

(4) Check the Show limits on plot button to interactively draw your baseline windows. You can click and drag the edges of these limit lines in the "Spectral plot" window.

(5) Check Enable for each new baseline window you want to define.

(6) Click Run.

Figure 10.1: Removing a baseline with GAIA
10.2 Creating channel maps with GAIA

You can display channel maps in GAIA by selecting the region of a spectrum you wish to collapse over. You can use a spectrum from any of the pixels in the cube and the region selected will be applied to the whole map.

(1) Select the spectrum you want to use as your template for the entire cube.

(2) Select the Chanmap tab in the "Display image sections of a cube" window.

(3) Check the Show limits on plot box to interactively draw the range over which to collapse your cube. You can click and drag the end-bars of the limit lines in the "Spectral plot" window.

(4) Select the collapse method (Max is chosen in the example).

(5) Use the slider bars to select the total number of channels you want to generate and the number of x-axis channels. The x-axis channel number sets the aspect ratio for the resulting display grid.

(6) Click Run. The result is shown in the figure below.

Figure 10.2: Creating a channel map with GAIA

10.3 Contouring with GAIA

(1) Open the map you wish to contour over.
(2) Select **Image-Analysis > Contouring** from the menu bar across the top of the main window.

(3) Select the file you wish to contour in the "Contouring" window.

(4) Generate your contours in the **Generate** tab found on the left-hand side of the "Contouring" window. The example below defines linearly spaced contours starting at 900K. Clicking the **Generate** button will return you to the Levels tab.

You can also input or edit the contour levels manually in the **Levels** tab.

(5) Customise the look of your contours under the **Options** menu. You can experiment with the other tabs (Region and Key) for options concerning contour area and legend.
Click the **Draw Contours** button to make the contours appear over your map in the main window. If you are contouring over a cube you can scroll through the velocity axis whilst the contours remain fixed on top.

To add a second set of contours select **File > New window** in the top menu of the "Contouring" window. Here you can define a second image to be contoured and specify new levels and appearance. Open as many new contouring windows as necessary.

To save the graphic, there is a **File > Print**, but some people prefer a tool with a capture facility such as **XV**.
10.4 Overlaying clumps and catalogues with GAIA

GAIA can display two- or three-dimensional clump catalogues that have been generated by the CUPID routine findclumps (see Section 9.5). Clump catalogues in this format are also available for download from the JCMT Science Archive.

1. Open your cube for three-dimensional clump finding or your integrated map for two-dimensional clump finding.

2. Select Image-Analysis > Positions > Import CUPID catalogue from the menu bar across the top of the main window. Note that for two-dimensional catalogues an alternative route is to select Data-Servers > Local catalogs. In this case you can skip Step 3.

3. In the "Import CUPID catalogue" window, select a file with the Choose file... button. For polygon shapes tick the STC shape box. You can change the RA/Dec co-ordinates from Cen1/Cen2, which give the central position of the clumps, to Peak1/Peak2 which give the position of the peak within them.

4. A catalogue window for your FITS file will appear listing all the sources and their positions and extents.
(5) Outlines of your clumps, or symbols at the peak positions, will be automatically overlaid on your map. If this does not happen, click the **Plot** button on the catalogue window. When you click on a clump from the catalogue list the outline of that clump will appear in bold on your map.

(6) If you are displaying a three-dimensional catalogue over a cube, it will only display clumps which include data from the current slice. The clumps shown will update as you move through the cube.
10.5 Displaying average spectrum with GAIA

(1) Select the Spectrum tab in the "Display image sections of a cube" window.

(2) Define the shape of your region by selecting one of the Define region buttons (a circle is chosen in the example below).

(3) Select the combination method (Mean is chosen in the example below).

(4) Draw the shape on your map by clicking and dragging the mouse. The "Spectral plot" window will automatically update to show your combined spectrum. You can re-position and resize your shape at any time. You can see from Figure 10.12 that the averaged spectrum gives a much clearer profile of the source.

Figure 10.11: Displaying an average spectrum with GAIA

Figure 10.12: (Left) Average of the spectra within the blue circle in the figure above. (Right) Single spectrum from the centre of the blue circle above.
10.6 Collapsing your cube with GAIA

(1) Select the axis you want to collapse over by selecting from the Axis drop-down list in the "Display image sections of a cube" window.

(2) Select the spectrum you want to use as a template for your cube.

(3) Select the Collapse tab in the "Display image sections of a cube" window.

(4) Check the Show limits on plot button to interactively select your collapse region. You can click and drag the edges of these limit lines in the "Spectral plot" window. Position these around the region you wish to collapse over.

(5) Select the collapse method via the Combination method drop-down list (Integ is selected in the example below).

(6) Click Run. The main window will automatically update to show your collapse image.

Figure 10.13: Collapsing your cube using GAIA

10.7 Three-dimensional visualisation with GAIA

(1) Select View>3D Visualisation>Isosurfaces.../Volume rendering in the "Display image sections of a cube" window.

(2) Click and drag the image display to change the orientation in the "Volume render" window.

(3) Include axes labelling, the image plane and other features using the check boxes on the side bar.
10.8 Sending spectra to SPLAT

`GAIA` has very limited analysis functionality for spectra. Whereas `SPLAT` is a sophisticated graphical spectral-analysis tool. Any spectrum displayed in `GAIA` (a single-position spectrum or a spectrum averaged over some region 10.5) can be sent (via a protocol called SAMP) to `SPLAT` for more-detailed spectral analysis.

`SPLAT` offers the ability to further process, fit, or identify spectral lines. You can also plot different spectra in the same window and make publishable files. The full `SPLAT` documentation can be found here in `SUN/243`.

Here are some instructions on how to do this.
(1) Start SPLAT if it is not already running.

    % splat &

(2) Click on the Interop menu item in SPLAT. If the SAMP control icon has a red circle, it means that the SAMP communication hub is running. If, however, the icon has a white circle, you need to start a hub. To do this press the Register with HUB button at the bottom of the window, and then press the Start internal hub button in the window that pops up.

(3) If you had GAIA already running before the hub was active, then in GAIA select the Interop > Register to register your GAIA with the hub.

(4) Select the spectrum you wish to send from GAIA.

(5) Click on SPLAT-VO Send: replace or Send: add button near the bottom of the "Display image sections of a cube" window. The spectrum should appear in a SPLAT window.

SAMP can also transmit images and catalogues between compliant applications. For example, you might have a selected catalogue of sources observed elsewhere in TOPCAT and want to plot the locations over your HARP maps in GAIA.
Chapter 11
Using SPLAT

SPLAT is a graphical spectral-analysis tool. SPLAT offers tools for further processing, fitting, or identification of spectral lines. One can also plot different spectra in the same window and make publishable files. The full SPLAT documentation can be found in SUN/243.

11.1 Opening a spectrum in SPLAT

There are two options for opening up a spectrum in SPLAT. First it is possible to send a spectrum to SPLAT using GAIA as described in Section 10.8. Alternatively spectra can be displayed in directly in SPLAT using:

```
% splat filename &
```

for a single position cube or

```
% splat 'filename(xpos,ypos,)' &
```

to display the spectrum at the pixel position (xpos,ypos). Or simply initialise SPLAT and open the file directly from the gui.

```
% splat &
```

When SPLAT is initially started you will get a main window appear and also a spectral window.

11.2 Display synopsis of spectrum

When you initially open a spectrum in SPLAT the synopsis of that spectrum will automatically be overlaid on the spectrum displayed, if the metadata are known to SPLAT. The following are a list of possible properties than can be displayed, with a brief description. Names in parenthesis are either the FITS keywords or AST attributes used to obtain the values.

1. Name: the short name
2. Telescope: telescope, instrument and its backend (TELESCOPE/INSTRUME/BACKEND)
3. Object: target, molecule and molecular transition being observed (OBJECT/MOLECULE/TRANSIT)
4. Date obs: date of the observation (DATE-OBS or Epoch in UTC)
5. Elevation: observatory elevation (ELSTART or 0.5*(ELSTART+ELEND))
Figure 11.1: The main SPLAT window and spectral window.

(6) Exposure: exposure time for the spectrum (EXTIME)
(7) Exposure (median): exposure time for the spectrum (EXP.TIME)
(8) Exposure (elapsed): the time elapsed during exposure (INT.TIME otherwise DATE-END — DATE-OBS)
(9) Exposure (effective): effective exposure time (EXEFFT)
(10) Coords sys: the co-ordinate system code (System)
(11) Spec position: position of spectrum on the sky (EXRAX, EXDECX)
(12) Src position: position of the observation centre (EXRRA, EXRDEC)
(13) Img centre: centre of the originating image (EXRA, EXDEC)
(14) Offset: offset of spectrum from the observation centre (EXRRAOF, EXRDECOF or EXRAOF, EXDECOF)
(15) Doppler RA Dec: reference position (RefRA,RefDec)
(16) SourceVel: source velocity (SourceVel)
(17) SourceVRF: source velocity reference frame (SourceVRF)
(18) SourceSys: system of the source velocity (SourceSys)
(19) StdOfRest: standard of rest (StdOfRest)
(20) RestFreq: rest frequency (RestFreq)
(21) ImageFreq: image sideband equivalent of the rest frequency (ImageFreq)
(22) Channel spacing: channel spacing (derived value)
(23) Number of channels: Number of co-ordinate positions
(24) TSYS: system temperature (TSYS)
(25) TSYS (median): median system temperature (MEDTSYS)
(26) TSYS (est): system temperature (derived value)
(27) TRX: receiver temperature (TRX)

To show or remove the synopsis of a spectrum simply click on the Options button in the spectral view window and select or deselect Display Synopsis. To move the position of the synopsis simply click and drag the text box to the desired location.

![Figure 11.2: How to display or remove the synopsis of a spectrum in the spectral window.]

11.3 Changing units of a spectrum in SPLAT

Sometime you may wish to change the units of a spectrum in SPLAT.

1. Click on Change the units of the current spectrum button in your current spectral window.
2. A new window will appear called "Current Spectrum Units".
3. From the Coordinates drop-down menu select the desired unit (in this case we select Kilometers-per-sec (radio)). Then click Apply.
4. You will now see that the spectrum is displayed in Radio Velocity (km/s).
Figure 11.3: Top: Select the **Change the units of the current spectrum** button. Note that in this example the current units are Frequency. Bottom: the "Current Spectrum Units" window.

Figure 11.4: Changing the units of the spectrum via the drop-down menu to km s\(^{-1}\).

### 11.4 Cropping a spectrum in SPLAT

1. Click on **Cut out the regions of the current spectrum** button above the spectrum you wish to work on. This will open a new window.
2. Select **Add** from the cut region window.
3. Click and drag the regions you wish to remove from the spectrum in the spectrum window. As we had a second region to remove we click on the **Add** button a second time. In this example we select...
the two noisy edge regions from the spectrum to remove.

(4) Select the **Remove Selected** button.

(5) A new spectrum with the noisy edges removed will now appear in the main **SPLAT** window. Click on your newly created spectrum to view.

### 11.5 Rebinning a spectrum in SPLAT

(1) Click on **Apply a filter to the current spectrum** button above the spectrum you wish to work on. This will open a new window.

(2) Select the number of channels over which you want to bin—this is the **Width**. In this example the spectrum has a resolution of 0.055 km s\(^{-1}\). We bin by 18 channels to rebin the spectrum to 1 km s\(^{-1}\) channels.

(3) Select **Filter (Replace)**. This will create a new spectrum in the main **SPLAT** window and will also replace the existing spectrum displayed in the spectral window with the new binned spectrum.

### 11.6 Estimating the noise in a spectrum using SPLAT

(1) Click on **Get statistics on region of spectrum** button above the spectrum you wish to work on. This will open a new window.

(2) Select **Add** from the ”**Region statistics**” window.

(3) Click and drag the regions you calculate the statistics over. As we wish to include baselines either side of the spectral line seen in the data we click on the **Add** button a second time.
(4) You will see the two selected spectral regions appear in a table in the "Region statistics" window with some basic statistic already computed for each region created.

(5) Click on Selected stats or All stats to get statistics of the regions combined. In this example we see the standard deviation in the regions selected is 0.19K.

### 11.7 Fitting a line in a spectrum using SPLAT

Your data might have lines for which you want a quick estimate of its line strength and width.

(1) Click on Fit spectral lines using a variety of functions button above the spectrum you wish to work on. This will open a new window.

(2) Click on the Add button in the "Measure spectral lines" window.

(3) Click and drag the box that appears in the spectral window to encompass the line for which you wish to calculate a fit for.
Figure 11.7: Top: The two regions selected. Bottom: remove the selected region by clicking the **Remove Selected** button.

(4) Click on the **Fit** button to produce both a **Quick** and **Gaussian** fit to the spectral line.

(5) We see the results of the fit are provided in the "Measure spectral lines" window, and the two fits can be seen in the spectral line window.
Figure 11.8: Top: Select the newly created spectrum in the main SPLAT window. The spectrum with the selected noisy-edge-data removed will then appear.
Figure 11.9: Top: The SPLAT "Filter regions of a spectrum" window. Bottom: The final rebinned spectrum.
Figure 11.10: Top: Select the statistics button. Bottom: Select the **Add** button.

Figure 11.11: Click and drag the regions over which you wish to estimate the noise.
Figure 11.12: Two spectral regions have been selected and are displayed in the "Region statistics" window.

Figure 11.13: Statistics for both regions are displayed in the "Region statistics" window.
Figure 11.14: Top: Select the spectral-fitting button. Bottom: Click on the Add button.
Figure 11.15: Click and drag the region containing the line which you wish to be fitted.

Figure 11.16: In the "Measure spectral lines" window, we see the both the Quick fit (black dashed line) and the Gaussian fit (pink line) of the spectral line.
Figure 11.17: In the spectral window we see both the **Quick** fit (black dashed line) and the **Gaussian** fit (pink line) of the spectral line.
Chapter 12
Getting your data from CADC

The JCMT Science Archive is hosted by The Canadian Astronomy Data Centre (CADC). Both raw data and data processed by the science pipeline are made available to PIs and co-Is through the CADC Advanced Search interface linked from the JCMT landing page (http://www3.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/jcmt/).

To access proprietary data you will need to have your CADC username registered by the EAO and thereby associated with the project code.

When searching the JCMT Science Archive, be sure to select the correct search option from the ‘JSA Queries’ tab. Here you can select public versus proprietary, raw versus reduced, and SCUBA-2 versus ACSIS data.

An important search option to be aware of is ‘Group Type’, where your options are Simple, Night, Project and Public. Simple (which becomes ‘obs’ on the result page) is an individual observation; night means the group file from the pipeline (these may or may not include more than one observation; the ‘Group Members’ value will tell you); and the project option is generated if an entire project has been run through the pipeline and identical sources across the project are co-added into master group files.

The format and file naming conventions are different in the JSA for reduced data compared with merely running ORAC-DR. Reduced observations will be in FITS format with the .fits file extension. File

![Screenshot of the CADC search window for reduced HARP data.](image)

Figure 12.1: Screenshot of the CADC search window for reduced HARP data.
names begin with the jcmth prefix followed by the UT date, observation number, subsystem number, the product name and subscan number, the grouping algorithm, and finally a version number (in practice zero), with adjacent elements separated by an underscore. The product name of most interest will be reduced, but others include rimg and rsp for the representative image and spectrum. The grouping algorithm is obs for a single observation, and nit where all the good data for an object observed with the same instrumental setup during a night are combined to create products of better quality. A further grouping is pro) where matching observations within a project are combined, which may extend over many nights spanning years.

Here is a are some examples: jcmth20070728_00066_01_reduced002_obs_000.fits, jcmth20070728_00066_01_rimg001_nit_000.fits, and jcmth20070728_00066_02_rsp001_pro_000.fits.

For a detailed guide to using the Advanced Search see JSA User’s Guide.
Bibliography


Appendix A
PICARD

There are two recipes which can be used with ACSIS data and are of general interest:

A.1 CREATE_MOMENTS_MAP

This recipe is used to create a moments maps from a cube. It smooths the cube in frequency and spatial extents, then uses the ClumpFind algorithm to find clumps of emission. Everything in the cube not found in a clump is masked out, then the masked cube is collapsed to form the moments map.

Recipe options:

- MOMENTS: Which moments maps to create (integ/iwc/itd) [integ]
- MOMENTS_LOWER: An optional lower velocity in km s\(^{-1}\), below which no data will be used when creating the moments map. [undef]
- MOMENTS_UPPER: An optional upper velocity in km s\(^{-1}\), above which no data will be used when creating the moments map. [undef]
- MOMENTS_SNR: Whether or not to do clump detection on a signal-to-noise cube instead of the signal cube. Enabling this is useful for data taken in varying conditions. [0]

A.2 MOSAIC_JCMT_IMAGES

This recipe co-add the given files into a single map while correctly handling the exposure time FITS header and other NDF components. The maps are combined using inverse-variance weighting and the output variance is derived from the input variances. You can choose either wcs mosaic or a combination of wcsalign and the CCDPACK application makemos to mosaic the images.

Recipe options:

- MOSAIC_EACH: Flag to indicate whether the data should be mosaicked by individual object or combined into a single output file.
- MOSAIC_TASK: Name of mosaicking task to use, wcs mosaic or makemos [wcs mosaic]
- MAKEMOS_METHOD: Image combination method for makemos, may be median (default), mean or sigmas. See CCDPACK manual for advice on choosing a method.
- MAKEMOS_SIGMAS: Sigma-clipping threshold if MAKEMOS_METHOD = sigmas. [4]
- MASK_LOWVAR: Flag to indicate that pixels with anomalously-low variances should be removed before mosaicking. [0]
- WCSMOSAIC_METHOD: wcs mosaic and wcsalign pixel-spreading method. [nearest]
- WCSMOSAIC_PARAMS: additional parameters that may be specified with wcs mosaic
A.3 Running PICARD recipes

There are a number of options available when running PICARD recipes. The example below illustrates most of them.

```
% picard -recpars params.ini MOSAIC_JCMT_IMAGES 'cat myfilelist.lis' -log sfx
```

- The recipe parameters are listed in a file called `params.ini`. It is called by the `recpars` option. This file has the same `.ini` format used by the ORAC-DR pipeline (see Section 6.2).
- The recipe name need to be in uppercase.
- If you need to supply multiple files you can do so by listing them in a file (`myfilelist.lis` in this example) and running `cat` on it. The input file must be in the current directory, or a directory defined by the environment variable `ORAC_DATA_IN`. Note the back-quotes.
- Like the ORAC-DR pipeline, the `-log` option specifies whether the log file should be written to the screen `[s]`, a file `[f]` or an xwindow `[x].

**Tip**

TIP: The `.sdf` extension on filenames is required by PICARD.

**Tip**

If the environment variable `ORAC_DATA_OUT` is defined, any files created by PICARD will be written in that location. Check there if new files are expected but do not appear in your working directory.
Appendix B
Converting file formats

B.1 Converting a FITS file to NDF
A FITS file can be converted to NDF using the Starlink package `CONVERT`. The `convert` instruction sets up the definitions for this package and only needs to be entered once,

```
% convert
```
the relevant one here being `fits2ndf`.

```
% fits2ndf file.fits file.sdf
```
Note that the `.sdf` file extension NDF may be omitted to save typing.

Unless your FITS file is from a recognised source, `fits2ndf` puts the various FITS extensions into NDF extensions called FITS_EXT_\(< n >\)\), where \( n \) counts from one for the first FITS extension. These are located in the top-level MORE component of the NDF. If one of these is the array you want—it should be an NDF too—it will be easier to handle if you copy out of the NDF extension to its own NDF.

```
% ndfcopy in=file.more.fits_ext_1 out=file_data
```
If there is a variance array stored in another extension that you want to attach to your new NDF, a command like the following will do that.

```
% setvar ndf=file_data from=file.more.fits_ext_2
```
fits2ndf does offer a way of mapping FITS extensions to familiar NDF array components DATA, VARIANCE, and QUALITY through the EXTABLE file, avoiding the `ndfcopy` and possible `setvar` steps.

B.2 Converting an NDF file to FITS
The `CONVERT` package can also be used to convert an NDF file to FITS format.

```
% convert
% ndf2fits file file.fits
```
There are options to control whether or not to export all of the NDF extensions (PROEXTS) and history records (PROHIS), and whether or not to merge the contents of the FITS airlock (PROFITS).

For historical reasons the specific set of headers encoding the world co-ordinate system varies from package to package. There is a parameter to select the appropriate encoding for the destination of the FITS file. A common one in the submillimetre world is the `CLASS` package used for spectroscopic reductions.

```
% ndf2fits ga20091011_37_1_reduced /* encoding=fits-class
```
This will create a `ga20091011_37_1_reduced.fit` file with the `CLASS`-style of WCS headers.
Appendix C
Scripting your reduction

You may wish to write a script to process your data rather than running each task independently. In this case your script should start with:

```bash
#!/bin/csh -f
source $STARLINK_DIR/etc/login >& /dev/null
source $STARLINK_DIR/etc/cshrc >& /dev/null
kappa >& /dev/null
```
Appendix D
Regridding versus resampling

Sometimes you may wish to put your data onto a new pixel-size scheme. This may either involve regridding (often called rebinning) the data onto larger pixel sizes, or resampling the data onto smaller pixels, both using KAPPA.

The key difference between rebinning and resampling is whether you iterate over the input or output pixels. Rebinning divides each input pixel value between a group of neighbouring output pixels, whereas resampling allocates each output pixel a value sampled from the input array.

resampling—Resampling of the grid of input data is performed by transforming the co-ordinates of the centre of each output pixel into the co-ordinate system of the input grid. Since the resulting co-ordinates will not, in general, coincide with the centre of an input pixel, sub-pixel interpolation is performed between the neighbouring input pixels. This produces a resampled value, which is then assigned to the output pixel. Since resampling does not integrate, the total data value in the input image will not, in general, be conserved. Resampling has the advantage of ensuring that the output image is filled (provided the input array contains good data).

rebinning—Rebinning of the grid of input data is performed by transforming the co-ordinates of the centre of each input pixel into the co-ordinate system of the output grid. The input pixel value is then divided up and assigned to the output pixels in the neighbourhood of the central output co-ordinates. A choice of schemes are provided for determining how each input pixel value is divided up between the output pixels. In general, each output pixel may be assigned values from more than one input pixel. All contributions to a given output pixel are summed to produce the final output pixel value. Rebinning can leave gaps in the output array if the output array’s pixels are smaller than those of the input array.
Appendix E
Clump-finding Algorithms

GaussClumps
Based on the algorithm described by Stutzki & Güsten (1990, ApJ 356, 513). This algorithm proceeds by fitting a Gaussian profile to the brightest peak in the data. It then subtracts the fit from the data and iterates, fitting a new ellipse to the brightest peak in the residuals. This continues until the integrated data sum in the fitted Gaussians reaches the integrated data sum in the input array, or a series of consecutive fits are made which have peak values below a given multiple of the noise level. Each fitted ellipse is taken to be a single clump and is added to the output catalogue. In this algorithm, clumps may overlap. Any input variance component is used to scale the weight associated with each pixel value when performing the Gaussian fit. The most significant configuration parameters for this algorithm are: GaussClumps.FwhmBeam and GaussClumps.VeloRes which determine the minimum clump size.

ClumpFind
Described by Williams et al (1994, ApJ 428, 693). This algorithm works by first contouring the data at a multiple of the noise, then searches for peaks of emission which locate the clumps, and then follows them down to lower intensities. No a priori clump profile is assumed. In this algorithm, clumps never overlap. Clumps which touch an edge of the data array are not included in the final list of clumps.

Reinhold
Based on an algorithm developed by Kim Reinhold at JAC. See SUN/255 for more information on this algorithm. The edges of the clumps are first found by searching for peaks within a set of one-dimensional profiles running through the data, and then following the wings of each peak down to the noise level or to a local minimum. A mask is thus produced in which the edges of the clumps are marked. These edges however tend to be quite noisy, and so need to be cleaned up before further use. This is done using a pair of cellular automata which first dilate the edge regions and then erode them. The volume between the edges are then filled with an index value associated with the peak position. Another cellular automata is used to removed noise from the filled clumps.

FellWalker
David Berry devised an algorithm that walks up hills along the line of greatest gradient until a significant peak is reached. It then assigns all pixels visited along the route to the clump associated with the peak. Such a walk is performed for every pixel in the data array which is above a specified background level.

See SUN/255 for more information on findclumps and a full list of the configuration options for each algorithm.
Appendix F
Viewing your data with KAPPA

This appendix offers a few examples of creating different types of plots using KAPPA. The applications highlighted here are display and contour for maps, and linplot and clinplot for spectra (See the KAPPA manual for more details).

The plotting attributes for each of these applications is controlled in the same way. For full details of all the formatting options as well as setting up your graphics device, see the ‘Plotting Styles and Attributes’ section in the KAPPA manual.

F.1 Setting up xwindows

- Clear my graphics window and reset default values.
  
  % gdclear

- Set my display device to xwindows.
  
  % gdset xw

- Create an xwindow of the desired dimensions.
  
  % xmake -width 1500 -height 1000 xwindows

- To create a display window which plots black on a white background, change the order of black and white in the palette list for your graphics device. Check this using gdstate.
  
  % gdstate

  Ensure white is entry 0 and black in entry 1.

  % palentry 0 White
  % palentry 1 Black

F.2 Format axes

- Use wcsattrib to set how your axes should be formatted. Here the format of the first and second axes is set to two decimal places for Galactic co-ordinates. Find out more about the Format attribute under wcsattrib in the KAPPA manual.
  
  % wcsattrib map set format"(1)" .2
  % wcsattrib map set format"(2)" .2

- For FK5 co-ordinates you can use the same method to set exactly how the co-ordinates should be displayed. The example below sets R.A. units to 0h00m00s and Dec. units to 00'00".
  
  % wcsattrib fk5map set format"(1)" ghms
  % wcsattrib fk5map set format"(2)" gdms
F.3 Plotting a two-dimensional image

- Display map.sdf. Do draw axes and a border, but do not draw a title or a grid. The default cut parameters for mode=scale include all the data.

```
% display map border axes style="drawtitle=0,grid=0" mode=scale
```

Depending on your default settings you may get a map like the one below.

![Map Image](image)

Figure F.1: First attempt at displaying an integrated map with KAPPA display.

- Re-draw calling a style file and changing the scaling.

```
% display integ.sdf axes style=^style.dat mode=scale low=0 high=100
```

Below is a copy of the style file (style.dat) used to make Figure F.2.

```
border=1
tickall=1
majticklen=0.01
drawtitle=0
color(axis)=white
color(numlab)=black
color(border)=black
color(ticks)=white
size(numlab)=1
size(textlab)=1.5
nogrid=1
textlabgap(1)=0.01
textlabgap(2)=0.01
```

- Make the colour scale negative and then replot.

```
% lutneg
% display integ.sdf axes style=^style.dat mode=scale low=0 high=100
```
Figure F.2: Displaying an integrated map with KAPPA display using a style file to format the plotting attributes.

Figure F.3: Reversing the colour scale in KAPPA display.

- There are a number of colour palettes available in Starlink. You can find them in the $STARLINK_DIR/bin/kappa/ directory.

  \% ls $STARLINK_DIR/bin/kappa/*lut.sdf

  You can create your own colour scheme using the KAPPA routine lutedit. See the KAPPA manual for more details.

- Replot in colour by selecting one of these palettes via the lut option.

  \% display integ.sdf axes style="style.dat mode=scale low=0 high=100 \ lut=$STARLINK_DIR/bin/kappa/random3_lut
F.4 Plotting spectra

- Plot the spectrum from cube.sdf at the position $l=60^\circ.87$, $b=0^\circ.18$. Use existing style.dat except override the text label size which is too big for these axes labels.

```plaintext
% linplot "cube(60.87,0.18,)", style="'^style.dat,size(textlab)=1'"
```

- Re-plot, but this time only show the velocity range 10 to 35 km s$^{-1}$. You can do it this way:

```plaintext
% linplot "cube(60.87,0.18,-10:50)", style="'^style.dat,size(textlab)=1'", mode=histogram
```
or using \texttt{xleft} and \texttt{xright}.

\begin{verbatim}
% linplot "cube(60.87,0.18,10:35)" style="'^style.dat,size(textlab)=1';" \
  mode=histogram xleft=10 xright=35 lmode="'Extend,15,15''
\end{verbatim}

In the example above, the additional option \texttt{lmode} is included. This sets how the upper and lower limits for the y-axis are defined. This example expands the minimum and maximum values by 15% of the data range. In additional extended, the available options are range, percentile and sigma.

![Figure F.6: Displaying a zoomed-in spectrum with KAPPA linplot.](image)

- To plot a second spectrum over this one, re-call \texttt{linplot} but with the \texttt{noclear} option to keep the original plot underneath. The formatting defaults to the last time \texttt{linplot} was run, but with the one-off temporary change of setting the colour of the line to red. The plus sign means the change will not be remembered next time \texttt{linplot} is run.

\begin{verbatim}
% linplot "cube2(60.87,0.18,-10:50)" mode=hist style="'colour(line)=red'" \ 
  noclear
\end{verbatim}

![Figure F.7: Displaying two super-imposed spectra with KAPPA linplot.](image)
F.5 Plotting a grid of spectra

- To plot multiple spectra from a cube you can use `clinplot`.

```
% clinplot "cube(61.06~5,0.15~4,10.:30.)" nokey style="style.dat reflabel \ specstyle='colour(textlab)=red,colour(numlab)=red'" mode=hist
```

This example plots a grid of $5 \times 4$ pixels around $l=61^\circ 06$ and $b=0^\circ 15$. Each spectrum has a range of 10 to $30 \text{ km s}^{-1}$. Note the decimal points are necessary for the spectral limits, otherwise the spectrum would extend from pixel co-ordinates 10 to 30. The `specstyle` option allows you to format the spectral axes inside the main plot. The formatting options are the usual plotting attributes. The flag `relabel` annotates the interior spectral axes.

![Figure F.8: Displaying a grid of spectra with `clinplot`]

F.6 Plotting two images side by side

- Create a $2 \times 1$ grid of frames.
% picgrid 2 1

• Select the first frame.
  % picsel 1

• Display integ.sdf in the first frame.
  % display integ axes style="style.dat" mode=scale low=0 high=100

• Select the second frame.
  % picsel 2

• Display subinteg.sdf, a cut-out of integ.sdf, in the second frame.
  % display subinteg axes style="style.dat" mode=scale low=0 high=100

F.7 Selecting a different graphics device

• You can view all available graphics devices with gdnames.
  % gdnames

• Instead of using gdset to define a new graphics device for all your applications, you can add the device option to select a different one for just this command. In the example below the output goes to a PostScript file called myplot.ps. The option pscol_l specifies landscape mode with colour. Setting a name for your output PostScript file is optional; if left unset it will default to pgplot.ps.
  % linplot "cube(60.85,0.18,-10:50)" mode=hist device="pscol_l;myplot.ps"
If you want to combine the results of several applications into a single plot, you need to specify an encapsulated PostScript device, e.g., epsf_l. Once you have run all the application you can stack your list of PostScript files to produce a single file.

```
% psmerge plot*.ps > final.ps
```

**Tip**

You can abbreviate any of the command-line options so long as the application can distinguish it from the other options. For example, mode=histogram can be abbreviated all the way to mode=h.
Appendix G
Classified Recipe Parameters

The recipes REDUCE_SCIENCE_NARROWLINE, REDUCE_SCIENCE_GRADIENT, REDUCE_SCIENCE_LINEFOREST, and REDUCE_SCIENCE_BROADLINE support the following parameters, except where noted. Recipe parameters should be supplied in an external file and called by the command line option -recpars <params.ini>. For an example recipe-parameter file see Section 6.2.

The parameters are classified for easier identification.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLUMP_METHOD</td>
<td>Method for identifying emission clumps: Clumpfind, Fellwalker, or Thresh.</td>
</tr>
<tr>
<td>CUBE_WCS</td>
<td>The co-ordinate system in which to regrid cubes.</td>
</tr>
<tr>
<td>FINAL_LOWER VELOCITY</td>
<td>Lower velocity limit for all the cube products.</td>
</tr>
<tr>
<td>FINAL_UPPER VELOCITY</td>
<td>Upper velocity limit for all the cube products.</td>
</tr>
<tr>
<td>ITERATIONS</td>
<td>Number of iterations. Further iterations refine the identification of emission to exclude from baseline subtraction. One iteration is usually sufficient.</td>
</tr>
<tr>
<td>PIXEL_SCALE</td>
<td>The pixel scale, in arcseconds, of cubes.</td>
</tr>
<tr>
<td>REBIN</td>
<td>Comma-separated list of velocity resolutions to rebin the final spectral cube. The rebinned cubes are in addition to the full-resolution cube. The last can be compressed too (cf. VELOCITY_BIN_FACTOR).</td>
</tr>
<tr>
<td>SPREAD_FWHM_OR_ZERO</td>
<td>Depending on the spreading method, this parameter controls the number of arcseconds at which the envelope of the spreading function goes to zero, or the full-width at half-maximum for the Gaussian envelope.</td>
</tr>
<tr>
<td>SPREAD_METHOD</td>
<td>The method to use when spreading each input pixel between a group of neighbouring output pixels when regridding cubes.</td>
</tr>
<tr>
<td>SPREAD_WIDTH</td>
<td>The number of arcseconds on either side of the output position which receive contributions from the input pixel.</td>
</tr>
<tr>
<td>VELOCITY_BIN_FACTOR</td>
<td>Average contiguous sets of velocity channels by this integer factor, each forming one channel in the reduced output. This compression is intended for the high-resolution ACSIS modes, to save significant storage and processing time, but it also yields better baseline subtraction.</td>
</tr>
</tbody>
</table>

Table G.1: The recipe parameters used to define the properties of the recipe products.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRACTION_BAD</td>
<td>The maximum fraction of bad values permitted in a receptor (or receptor’s subband for a hybrid observation) permitted before the receptor is deemed to be bad.</td>
</tr>
<tr>
<td>RESTRICT_LOWER_VELOCITY</td>
<td>Trims all data to this lower velocity, not just at the end for the products.</td>
</tr>
<tr>
<td>RESTRICT_UPPER_VELOCITY</td>
<td>Trims all data to this upper velocity, not just at the end for the products.</td>
</tr>
<tr>
<td>TRIM_MINIMUM_OVERLAP</td>
<td>The minimum number of desired channels that should overlap after trimming hybrid-mode observations.</td>
</tr>
<tr>
<td>TRIM_PERCENTAGE</td>
<td>The percentage of the total frequency range to trim from either end. This parameter only takes effect if both TRIM_PERCENTAGE_LOWER and TRIM_PERCENTAGE_UPPER are undefined.</td>
</tr>
<tr>
<td>TRIM_PERCENTAGE_LOWER</td>
<td>The percentage of the total frequency range to trim from the lower end of the frequency range.</td>
</tr>
<tr>
<td>TRIM_PERCENTAGE_UPPER</td>
<td>The percentage of the total frequency range to trim from the higher end of the frequency range.</td>
</tr>
</tbody>
</table>

Table G.2: The recipe parameters used to exclude areas of noisy spectrum or bad receptors.

There are a number of ways to define the baseline regions:

- as a percentage of the spectrum width at either end of the spectrum (see BASELINE_EDGES);
- as a set of velocity ranges expected or known to be free of emission lines (see BASELINE_REGIONS); or if both of these arguments of corresponding recipe parameters is undefined,
- use the whole spectrum smoothing spectrally and spatially (see FREQUENCY_SMOOTH and SPATIAL_SMOOTH) with feature detection to mask lines (see BASELINE_METHOD).

The first two are suitable for broadline emission. The second is desirable in the presence of many lines. The third is the default and most appropriate for a single narrow line.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASELINE_EDGES</td>
<td>Percentage of the full range to fit on either edge of the spectra for baselining purposes. If set to a non-positive value and BASELINE_REGIONS is undefined, then the baseline is derived after smoothing and automatic emission detection. If assigned a negative value, BASELINE_REGIONS, if it is defined, will be used instead to specify where to determine the baseline.</td>
</tr>
<tr>
<td>BASELINE_METHOD</td>
<td>Source of the baseline region. Currently only auto is recognised. This requests the automated mode where the emission is detected and masked before baseline fitting. Otherwise BASELINE_EDGES or BASELINE_REGIONS (q.v.) will be used.</td>
</tr>
<tr>
<td>BASELINE_NUMBIN</td>
<td>The number of channels to which the spectral axis is compressed for automated masking of emission when BASELINE_METHOD=auto.</td>
</tr>
<tr>
<td>BASELINE_ORDER</td>
<td>The polynomial order to use when baselining cubes.</td>
</tr>
<tr>
<td>BASELINE_REGIONS</td>
<td>A comma-separated list of velocity ranges each in the format (v1 : v2), from where the baseline should be estimated. It is countermanded should BASELINE_EDGES be positive. These can also be used to define where to test baseline linearity if BASELINE_LINEARITY_LINEWIDTH is set to base.</td>
</tr>
<tr>
<td>FREQUENCY_SMOOTH</td>
<td>The number of channels to smooth in the frequency axis when smoothing to determine baselines. This number should be small (~10) for narrow-line observations and large (~25) for broad-line observations.</td>
</tr>
<tr>
<td>SPATIAL_SMOOTH</td>
<td>The number of pixels to smooth in both spatial axes when smoothing to determine baselines.</td>
</tr>
</tbody>
</table>

Table G.3: The recipe parameters to control how baselines are determined and fit.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV_IMAGE</td>
<td>Permits creation of a longitude-velocity map via primitive <em>CREATE_LV_IMAGE</em>.</td>
</tr>
<tr>
<td>LV_AXIS</td>
<td>Specify the axis to collapse in the creation of the longitude-velocity map.</td>
</tr>
<tr>
<td>LV_ESTIMATOR</td>
<td>Specify the collapse statistic in the creation of the longitude-velocity map.</td>
</tr>
<tr>
<td>CREATE_MOMENTS_USING_SNR</td>
<td>If set to true (1), moments maps will be created using a signal-to-noise map to find emission regions. This is useful when observations were taken under differing sky conditions and have different noise levels.</td>
</tr>
<tr>
<td>MOMENTS</td>
<td>Comma separated list of the moments maps to create (integ,iwc).</td>
</tr>
<tr>
<td>MOMENTS_LOWER VELOCITY</td>
<td>The lower velocity range from which the moments maps will be created.</td>
</tr>
<tr>
<td>MOMENTS_UPPER VELOCITY</td>
<td>The upper velocity range from which the moments maps will be created.</td>
</tr>
</tbody>
</table>

Table G.4: The recipe parameters used to specify moments and longitude-velocity products.
### Table G.5: The recipe parameters associated flat fielding.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLATFIELD</td>
<td>Whether or not to perform flat-fielding.</td>
</tr>
<tr>
<td>FLAT_APPLY</td>
<td>Whether or not to apply the calculated flatfield. If set false the ratios are still calculated and logged.</td>
</tr>
<tr>
<td>FLAT_METHOD</td>
<td>Flatfield option to ratio voxel by voxel.</td>
</tr>
<tr>
<td>FLAT_LOWER</td>
<td>Sets the lower limit by which to restrict the velocity range where there is astronomical signal for FLAT_METHOD.</td>
</tr>
<tr>
<td>FLAT_UPPER</td>
<td>Sets the upper limit by which to restrict the velocity range where there is astronomical signal for FLAT_METHOD.</td>
</tr>
<tr>
<td>MINSNR</td>
<td>Allow selection of higher signal-to-noise voxels for FLAT_METHOD.</td>
</tr>
</tbody>
</table>

### Table G.6: The recipe parameters associated removal of noise spikes.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DESPIKE</td>
<td>Whether or not to perform despiking.</td>
</tr>
<tr>
<td>DESPIKE_BOX</td>
<td>The size, in pixels, of the box used to both find the &quot;background&quot; and for cleaning spikes.</td>
</tr>
<tr>
<td>DESPIKE_CLIP</td>
<td>The clip standard deviations to use when finding spikes in the background-subtracted RMS spectrum.</td>
</tr>
<tr>
<td>DESPIKE_PER_DETECTOR</td>
<td>If a spike is not seen in all detectors, consider setting this value to 1.</td>
</tr>
</tbody>
</table>

### Table G.7: The recipe parameters used to limit computer memory requirements for large datasets or observation fields of view.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHUNKSIZE</td>
<td>Maximum sized chunk used for the group cube.</td>
</tr>
<tr>
<td>CUBE_MAXSIZE</td>
<td>Controls the maximum size of the reduced cube.</td>
</tr>
<tr>
<td>TILE</td>
<td>A true value (1) performs tiling of the cube to restrict the memory requirements. Such tiled cubes abut each other in pixel co-ordinates and may be pasted together to form the complete spectral cube.</td>
</tr>
<tr>
<td>Parameter</td>
<td>Description</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>HIGHFREQ_INTERFERENCE</td>
<td>If set to true (1) the spectra for each receptor are analysed to detect high-frequency interference noise, and those spectra deemed too noisy are excluded from the reduced products.</td>
</tr>
<tr>
<td>HIGHFREQ_INTERFERENCE_EDGE_CLIP</td>
<td>Used to reject spectra with high-frequency noise. It is the standard deviation to clip the summed-edginess profile iteratively in order to measure the mean and standard deviation of the profile unaffected by bad spectra.</td>
</tr>
<tr>
<td>HIGHFREQ_INTERFERENCE_THRESH_CLIP</td>
<td>Used to reject spectra with high-frequency noise. This is the number of standard deviations at which to threshold the noise profile above its median level.</td>
</tr>
<tr>
<td>HIGHFREQ_RINGING</td>
<td>Whether or not to test for high-frequency ringing in the spectra. This is where a band of spectra in the time series have the same oscillation frequency and origin with smoothly varying amplitude over time.</td>
</tr>
<tr>
<td>HIGHFREQ_RINGING_MIN_SPECTRA</td>
<td>Minimum number of good spectra for ringing filtering to be attempted (see HIGHFREQ_RINGING). The filter needs to be able to discriminate between the normal unaffected spectra from those with ringing. The value should be at least a few times larger than the number of affected spectra.</td>
</tr>
</tbody>
</table>

Table G.8: The recipe parameters associated exclusion of spectra affected by high-frequency noise.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOWFREQ_INTERFERENCE</td>
<td>If set to true (1), the spectra for each receptor are analysed to detect low-frequency local interference ripples or bad baselines, and those spectra deemed too deviant from linearity are excluded from the reduced products.</td>
</tr>
<tr>
<td>LOWFREQ_INTERFERENCE_EDGE_CLIP</td>
<td>Used to reject spectra with low-frequency interference. It is the standard deviation to clip the profile of summed-deviations from linearity iteratively in order to measure the mean and standard deviation of the profile unaffected by bad spectra. A comma-separated list will perform iterative sigma clipping of outliers, but standard deviations in the list should not decrease.</td>
</tr>
<tr>
<td>LOWFREQ_INTERFERENCE_MAX_THRESHOLD</td>
<td>Spectra are deemed to be non-linear if their non-linearity exceeds this threshold.</td>
</tr>
<tr>
<td>LOWFREQ_INTERFERENCE_MIN_THRESHOLD</td>
<td>No spectra with non-linearity below this threshold will be rejected.</td>
</tr>
<tr>
<td>LOWFREQ_INTERFERENCE_THRESH_CLIP</td>
<td>Used to reject spectra with low-frequency interference. This is the number of standard deviations at which to threshold the non-linearity profile above its median level.</td>
</tr>
</tbody>
</table>

Table G.9: The recipe parameters associated exclusion of spectra affected by non-linear baselines. These are for short periods during an observation where some external signal has affected the baselines. If most or whole of an observation might be affected see BASELINE_LINEARITY and related parameters below. These parameters are not available in the REDUCE_SCIENCE_BROADLINE recipe.
### Table G.10: The recipe parameters associated exclusion of receptors affected by non-linear baselines throughout or most of an observation. The parameters are not available in the `REDUCE_SCIENCE_BROADLINE` recipe.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASELINE_LINEARITY</td>
<td>If set to true, receptors with mostly or all non-linear baselines are excluded from the reduced products.</td>
</tr>
<tr>
<td>BASELINE_LINEARITY_CLIP</td>
<td>This is used to reject receptors that have non-linear baselines. It is the maximum number of standard deviations above the median rms deviations for which a detector’s non-linearity is regarded as acceptable.</td>
</tr>
<tr>
<td>BASELINE_LINEARITY_LINEWIDTH</td>
<td>This is used to reject receptors that have non-linear baselines. It is the extent of the source spectral line measured in $\text{km s}^{-1}$, which is excluded from the non-linearity tests.</td>
</tr>
<tr>
<td>BASELINE_LINEARITY_MINRMS</td>
<td>This is used to retain receptors that have noisy or slightly non-linear baselines, or transient bad baselines (cf. LOWFREQ_INTERFERENCE). The parameter is the minimum rms deviation from linearity, measured in antenna temperature, for a receptor to be flagged as bad.</td>
</tr>
<tr>
<td>BASELINE_LINEARITY_SCALELENGTH</td>
<td>This is used to reject receptors that have non-linear baselines. It is the smoothing scale length in whole pixels. Features narrower than this are filtered out during the background-level determination. It should be should be odd and sufficiently large to remove the noise while not removing the low-frequency patterns in the spectra.</td>
</tr>
</tbody>
</table>

### Table G.11: The recipe parameters associated with calibration of the data. The sideband-ratio-correction recipe parameters are used for controlling the sideband correction, and are currently only available for instrument RxA3M. These corrections do not affect reductions done with `REDUCE_SCIENCE_CONTINUUM`, but will be used in all other RxA3M science reductions, and in the `PICARD` recipe `CALIBRATE_SIDEBAND_RATIO`. The `CALCULATE_STANDARD_ALWAYS` flag will also affect the non-continuum recipes.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CALCULATE_STANDARD_ALWAYS</td>
<td>If set true (1), this will ensure that the log. standard file will be created even if the source, molecule, and transition combination is not present in the list of known standard sources. This will affect most non-continuum heterodyne recipes.</td>
</tr>
<tr>
<td>NOSIDEBANDCORR</td>
<td>If set to 1, this will prevent any sideband-calibration correction factor from being applied to the data.</td>
</tr>
<tr>
<td>SIDEBAND</td>
<td>Set the sideband (e.g. USB or LSB) to use when applying the sideband correction. By default the system will use the sideband of the observation, but this recipe parameter can override that default if you are interested in a line in the image sideband.</td>
</tr>
<tr>
<td>SIDEBAND_CORR_FACTOR</td>
<td>This allows you to override the sideband-correction factor chosen from the calibration system and provide your own. The data will be multiplied by the value you provide, so you must ensure it is appropriate for the given sideband and LO frequency of your data. The factor should be supplied in floating point.</td>
</tr>
<tr>
<td>Parameter</td>
<td>Description</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>SUBTRACT_REF_EMISSION</td>
<td>If true, the recipe will attempt to locate and remove reference (off-position) signal that appears as absorption lines.</td>
</tr>
<tr>
<td>REF_EMISSION_BOXSIZE</td>
<td>The width (in channels) of the largest reference-spectrum line expected, used to find the background before finding spectral lines. If no value is supplied, an iterative approach determines the largest line width.</td>
</tr>
<tr>
<td>REF_EMISSION_COMBINE_DETECTORS</td>
<td>If true, combine all detectors to form the reference spectrum. While it can improve the signal to noise, receptors are strictly viewing slightly different locations and hence each receptor’s reference spectrum will be different.</td>
</tr>
<tr>
<td>REF_EMISSION_COMBINE_REFPOS</td>
<td>Whether to combine observations by their reference position (1), or by observation date (0).</td>
</tr>
<tr>
<td>REF_EMISSION_MASK_SOURCE</td>
<td>This controls the use of the mask of source emission already detected for baseline estimation. There are pros and cons both using the mask (1) or not using it (0). The final option, Both, attempts to combine the benefits of both methods: the masked spectrum locates the lines, but the unmasked modal spectrum determine the line strengths.</td>
</tr>
<tr>
<td>REF_EMISSION_REGIONS</td>
<td>Instead of automated identification of absorption lines, supply a comma-separated list of line extents (v1:v2). These regions are masked and interpolated, the background determined and subtracted from the unmasked representative spectrum to form an approximation to the reference spectrum.</td>
</tr>
<tr>
<td>SUBTRACT_REF_SPECTRUM</td>
<td>If true, the recipe will interpolate across the extents of reference (off-position) lines that you specify, applied to each (reference position or date and/or detector) median spectrum to estimate the respective reference spectrum.</td>
</tr>
<tr>
<td>REF_SPECTRUM_COMBINE_DETECTORS</td>
<td>If true, combine all detectors to form the reference spectrum. While it can improve the signal to noise, receptors are strictly viewing slightly different locations and hence each receptor’s reference spectrum will be different.</td>
</tr>
<tr>
<td>REF_SPECTRUM_COMBINE_REFPOS</td>
<td>Whether to combine observations by their reference position (1), or by observation date (0).</td>
</tr>
<tr>
<td>REF_SPECTRUM_REGIONS</td>
<td>A comma-separated list of line extents (v2:v2) of the locations of absorptions lines to excise.</td>
</tr>
</tbody>
</table>

Table G.12: The recipe parameters associated with the filtering of reference-spectrum absorption-line artefacts, either automatically or specified manually. These methods are still experimental, although the manual identification is more reliable for known lines. Therefore these parameters are currently available only in the REDUCE_SCIENCE_NARROWLINE recipe.
# Appendix H

## Quality Assurance Parameters

Quality assurance parameters are supplied via the command line option `-cal qaparams=qa.ini`. For an example QA parameters file see Section 6.3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BADPIX_MAP</td>
<td>Maximum fraction of pixels allowed to be bad in the final map.</td>
</tr>
<tr>
<td>GOODRECEP</td>
<td>Minimum number of working receptors</td>
</tr>
<tr>
<td>TSYSBAD</td>
<td>Upper limit of $T_{sys}$ for raw time-series data.</td>
</tr>
<tr>
<td>FLAGTSYSBAD</td>
<td>Flag any receptor with $&gt;\text{FLAGTSYSBAD}$ of data points with $T_{sys} &gt; \text{TSYSBAD}$</td>
</tr>
<tr>
<td>TSYSMAX</td>
<td>Median $T_{sys} &gt; $ per receptor after flagging by FLAGTSYSBAD must be $&lt; \text{TSYSMAX}$</td>
</tr>
<tr>
<td>TSYSVAR</td>
<td>Maximum allowable receptor-to-receptor $T_{sys}$ variation</td>
</tr>
<tr>
<td>RMSVAR_RCP</td>
<td>Maximum allowable receptor-to-receptor RMS variation</td>
</tr>
<tr>
<td>RMSVAR_SPEC</td>
<td>The average rms noise shall not vary by more than RMSVAR_SPEC from one end of a spectrum to the other.</td>
</tr>
<tr>
<td>RMSVAR_MAP</td>
<td>The rms noise in the map over the region with uniform sampling shall not vary by more than RMSVAR_MAP from one pixel to the next.</td>
</tr>
<tr>
<td>RMSTSYSTOL</td>
<td>The rms that is measured for each receptor should agree with the value expected from the system temperature, spectral resolution, and integration time to within RMSTSYSTOL.</td>
</tr>
<tr>
<td>RMSMEANTSYSTOL</td>
<td>Data with an RMS $&gt; \text{RMSMEANTSYSTOL}$% of the mean RMS will get masked out.</td>
</tr>
<tr>
<td>CALPEAKTOL</td>
<td>Observations of the spectral-line calibrators shall agree with their expected values for line peak intensity to within $\pm \text{CALPEAKTOL}$.</td>
</tr>
<tr>
<td>CALINTTOL</td>
<td>Observations of the spectral-line calibrators shall agree with their expected values for integrated intensities to within $\pm \text{CALINTTOL}$.</td>
</tr>
<tr>
<td>RESTOL</td>
<td>Remaining residuals after subtraction of the baseline shall be no larger than $\sigma \times \text{RESTOL}$ on average.</td>
</tr>
<tr>
<td>RESCHAN12CO</td>
<td>Channels over which to average for residuals for a first line ($^{12}\text{CO}$ here).</td>
</tr>
<tr>
<td>RESCHAN13CO</td>
<td>Channels over which to average for residuals for a second line ($^{13}\text{CO}$ here).</td>
</tr>
<tr>
<td>RESTOL_SM</td>
<td>Remaining residuals should be no larger than $\sigma \times \text{RESTOL_SM}$ on average over any four adjacent channels.</td>
</tr>
<tr>
<td>VELRES_12CO</td>
<td>Velocity resolution for the first line ($^{12}\text{CO}$ here).</td>
</tr>
<tr>
<td>VELRES_13CO</td>
<td>Velocity resolution for the second line ($^{13}\text{CO}$ here).</td>
</tr>
</tbody>
</table>