XMM-Newton

Users Guide to the XMM-Newton Science Analysis System

Issue 18.0
Prepared by the
XMM-Newton Science Operations Centre Team

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Glossary

Acronym	Explanation
CAL	Calibration Access Layer
CAMEX	Multichannel readout chip
CCD	Charge Coupled Device
CCF	Current Calibration File
CIF	Calibration Index File
CTE	Charge Transfer Efficiency
CTI	Charge Transfer Inefficiency
DAL	Data Access Layer
DEC	Declination, δ(J2000)
EPIC	European Photon Imaging Camera
FITS	Flexible Image Transport System
FOV	Field Of View
FWHM	Full Width at Half Maximum
GO	Guest Observer
GTI	Good Time Interval
GUI	Graphical User Interface
HEASARC	(NASA) High Energy Astrophysics Science Archive Research Centre
MOS	Metal Oxide Semi-conductor CCD camera
OAL	ODF Access Layer
OCB	On-Chip Binning
ODF	Observation Data File
OGIP	(NASA) Office of the Guest Investigator Program
OM	Optical Monitor
OSW	Observed Science Window
QLA	Quick Look Analysis
PHA	Pulse Height Analyser (uncalibrated spectral channel)
PI	Pulse-Invariant (calibrated spectral channel)
PPS	Pipeline Processing Subsystem
PSF	Point-Spread Function
RA	Right Ascension, α(J2000)
RGA	Reflection Grating Assembly of the RGS
RGS	Reflection Grating Spectrometer
SAS	Science Analysis System
SDF	Slew Data File
SOC	XMM-Newton Science Operations Centre
SSC	Survey Science Centre
UHB	XMM-Newton Users Handbook
WCS	World Coordinate System
XMM-Newton	X-ray Multi-Mirror telescope
XSA	XMM-Newton Science Archive

1 Introduction

The purpose of this document is to guide and help the user with XMM-Newton data reduction. Data for a given XMM-Newton observation comprise a large number of products, mainly the raw and calibrated event files of the instruments on-board XMM-Newton: the European Photon Imaging Cameras (EPIC), the Reflection Grating Spectrometers (RGS) and the Optical Monitor (OM).

Full analysis of XMM-Newton data includes a quick look analysis of the raw data, calibration of raw event datasets, screening of calibrated data, extraction of images and spectra, extraction of time series, source detection and scientific analysis of the calibrated products. A large fraction of these tasks has to be conducted with the XMM-Newton Scientific Analysis System (SAS), the main analysis tool for XMM-Newton data reduction. SAS has been developed by a team of scientists located at ESA's XMM-Newton Science Operations Centre (SOC) and at the XMM-Newton Survey Science Centre (SSC). All the information available on the latest SAS version can always be found in the **SAS Web Portal** located at the following URL:

`http://www.cosmos.esa.int/web/xmm-newton/sas`

Any kind of problem or general question regarding SAS should be reported to the XMM-Newton HelpDesk:

`http://www.cosmos.esa.int/web/xmm-newton/xmm-newton-helpdesk`

1.1 SAS installation

The first step in the installation procedure is to identify the operating system and corresponding SAS release. SAS is supplied as a single *tgz* archive. Help on how to download SAS can be found at the SAS download web page:

`http://www.cosmos.esa.int/web/xmm-newton/sas-download`

This page provides a table showing the different builds and supported Operating Systems available for each SAS release. Once the *tgz* archive corresponding to a given SAS build has been downloaded, the installation process is quite straightforward and platform independent. Detailed installation instructions can be found at:

`http://www.cosmos.esa.int/web/xmm-newton/sas-installation`

SAS can be installed everywhere in your system. If */top_dir* is the directory selected to install the SAS, the single *tgz* archive should be unpacked there. The unpacking provides, among other files, a script named *install.sh*, which must be run to perform the installation. Once the installation is complete, the correspondent SAS release will be located in a subdirectory named:

```
xmmsas_YYYYMMDD_HHMM
```

which identifies uniquely each SAS release by the date (YYYYMMDD) and time (HHMM) of its production. Important changes to each SAS release are included in XMM-Newton SAS Release Notes [7].

The installation script will produce two additional shell scripts within the same directory, named *setsas.sh* and *setsas.csh* for the Bourne/Bash/Korn shells and csh/tcsh shells respectively. The purpose of these scripts is to initialize the SAS environment for each particular shell.

The *install.sh* script makes some checks to the shell environment before completing the installation:

- Whether perl is available or not in the PATH.
- Whether the environment variable SAS_PERL is defined or not and whether it is set to the same perl available through the PATH.
- Whether python is available or not in the PATH and whether the version of such python is the proper one or not.

If any of these checks is not fulfilled, the script produces an error message and interrupts the installation. Once the missing requirement is fulfilled, the installation can be resumed by running the script *xmmsas_YYYYMMDD_HHMM/configure_install*.

The installation script completes the installation changing the she-bangs of all the SAS Perl procedures to */usr/bin/env perl*.

See the following link for more information on any additional requirements:

`http://www.cosmos.esa.int/web/xmm-newton/sas-requirements`

1.2 More information on the web

It is assumed that the SAS user is familiar with the basic characteristics and operation modes of the scientific instruments on board XMM-Newton. This information is available in the XMM-Newton User Handbook [3].

Another important document is the XMM-Newton Data File Handbook [29], which provides a detailed description on the format, structure and content of the XMM-Newton files distributed to users from the XMM-Newton Science Archive (XSA) [4].

Detailed descriptions of individual SAS tasks can be accessed in several ways: through the SAS on-line documentation web page [6], by passing the *-m* option when running a particular SAS task, or by clicking the "Help Task" button of the (main) SAS Graphical User Interface (GUI), discussed in detail in § 3.

Last, issues concerning SAS and XMM-Newton data analysis are reported in the SAS watchout pages, along with recommended workarounds and/or solutions, and useful tricks and tips:

`http://www.cosmos.esa.int/web/xmm-newton/sas-watchout`

1.3 SAS Analysis Threads

SAS Analysis Threads are simple examples intended to help users, in particular beginners, to reduce and analyse XMM-Newton data. They cover from the basic system set-up to the most complex analysis topics.

SAS Analysis Threads are revised to reflect the latest changes in the current SAS release, and new threads are added as new functionality or tools become available in SAS.

Some of the analysis procedures described in this guide are also applied and explained in the SAS Analysis Threads [32] web pages.

1.4 Structure of the document

The structure of the present document is as follows:

- Chapter 2 introduces the investigator to the analysis of XMM-Newton data. It provides a brief description of XMM-Newton observation and calibration files and outlines the analysis steps required to produce calibrated event files and to extract scientific products.
- Chapter 3 describes the SAS graphical user interface (GUI), a user friendly tool which enables SAS interactive analysis tasks to be run without using the command line.
- Chapters 4, 5 and 6 describe the SAS analysis steps required to obtain EPIC, RGS and OM data products, respectively, which can be used afterwards by standard astronomical software packages.
- Chapter 7 gives an overview of a SAS procedure to produce high-level science products for XMM-Newton cameras from the raw, uncalibrated, data files contained in the Observation Data File (ODF). The procedure allows for some interactivity which lets the user take decisions concerning the analysis process.

2 Analysis of XMM-Newton data: an overview

2.1 XMM-Newton data files

The full set of XMM-Newton data files, corresponding to a given XMM-Newton observation, is basically composed of:

- the observation data files (ODF): these files include raw event science files from the EPIC, RGS and OM instruments, instrument housekeeping files, radiation monitor files and spacecraft files. Tables 3, 6 and 10 show the list of relevant data file identifiers for EPIC, RGS and OM respectively.
- all the data products generated by the Pipeline Processing Subsystem (PPS) at the XMM-Newton Science Operations Centre (SOC). A complete general description of the PPS products is given in the Pipeline Products Description document. Tables 4, 9 and 12 show the list of relevant pipeline product file identifiers corresponding to EPIC, RGS and OM respectively.

Both sets of data can be retrieved from the XMM-Newton Science Archive (XSA) [4].

In addition, and in order to carry out the analysis of the data, a set of what are known as Current Calibration Files (CCF) is necessary. These CCFs are available from the XMM-Newton web server at:

`http://www.cosmos.esa.int/web/xmm-newton/current-calibration-files`

For each CCF, its respective Release Notes can be found at:

`http://www.cosmos.esa.int/web/xmm-newton/ccf-release-notes`

The XMM-Newton ODFs and CCFs are compliant with the Flexible Image Transport (FITS) standard. A detailed description of their format, structure, naming convention and contents is provided in the XMM-Newton Data File Handbook [29] and the documentation of the XMM-Newton Current Calibration Files [30].

2.2 Steps in the analysis of XMM-Newton data. Threads and Watchout items

In general, the analysis of XMM-Newton data is composed of several steps.

1. Preparation of the analysis environment, including the access to XMM-Newton data and CCFs, the Science Analysis System (SAS) and the associated software tools.
2. Inspection of XMM-Newton ODFs and CCFs and pipeline products (PPS).
3. Creation of the Calibration Index File (CIF) and the ODF summary file (**SUM.SAS*).
4. Definition and planning of the analysis activities.
5. Creation of calibrated event lists using the SAS pipeline processing meta-tasks. The user may skip this step and use the calibrated event lists provided by the pipeline

products. This step will however be necessary if more up-to-date CCFs or SAS version have become available since the generation of the pipeline products.

6. Data screening, source detection and extraction of scientific products, including images, spectra and time series. To generate spectral products it is necessary to generate response files. Scientific products are also part of the pipeline products.

The completion of steps 2, 3, 5 and 6 require the use of tasks which are specific to SAS.

Before starting the process of data analysis, users are strongly encouraged first to have a look at the **SAS Analysis Threads**, where detailed examples are provided for the data reduction of each instrument, and to check regularly the **Watchout items and evergreen tips**, both under:

`https://www.cosmos.esa.int/web/xmm-newton/sas-watchout`

2.3 Starting a SAS session

2.3.1 Setting up the basic SAS environment

Prior to starting a new SAS session, the SAS environment has to be initialized. This is done by means of one of the shell scripts created during the SAS software installation process (*setsas.[c]sh*; see § 1.1). The way this is done depends on the shell used. Assuming that the SAS software installation was done at:

```
/top_dir/xmmsas_YYYYMMDD_HHMM
```

the script can be executed as follows:

```
. /top_dir/xmmsas_YYYYMMDD_HHMM/setsas.sh  [sh, bash, ksh]

or

source /top_dir/xmmsas_YYYYMMDD_HHMM/setsas.csh [csh, tcsh]
```

It is recommended to work in a directory different from that where SAS was installed. This way, analysis products do not mix with the SAS installation files.

The *setsas.[c]sh* script takes care of all the necessary environment setup required to work with SAS.

Some external tools are required to work with SAS. The URL,

`http://www.cosmos.esa.int/web/xmm-newton/sas-requirements`

provides detailed information on the tools needed and the versions required for a given SAS release. In recent versions of SAS, the *HEASOFT* software must be initialized prior to the initialization of SAS. Otherwise the SAS initialization will not be complete. Before the data analysis process can start, SAS has to know where the ODF and CCFs are.

2.3.2 Telling SAS where to find the ODF and CCF files

The `SAS_ODF` environment variable must point to the directory where the ODF of the observation to be analyzed is located:

```
export SAS_ODF=/path/to/<ODF> [sh, bash, ksh]

setenv SAS_ODF /path/to/<ODF> [csh, tcsh]
```

The `SAS_CCFPATH` environment variable must point to the directory where the SAS CCFs are stored:

```
export SAS_CCFPATH=/path/to/<CCF> [sh, bash, ksh]

setenv SAS_CCFPATH /path/to/<CCF> [csh, tcsh]
```

It is recommended to store all CCFs in a shared accessible directory so that other SAS users may refer to them.

2.3.3 cifbuild

A detailed description of the way in which the CCFs corresponding to a certain observation data set can be accessed, along with the parameters that need to be specified, can be found in § 3.11. The SAS command `cifbuild` retrieves the observation date from the observation to be analyzed and selects the calibration files for that given time period. Alternatively, the user can specify a given date for the CCFs to be used through one of the input parameters of the `cifbuild` task. All the different CCFs are kept in a repository accessible to the SAS user for building the calibration database.

Calling `cifbuild` with no parameters assumes the following defaults:

```
cifbuild calindexset = 'ccf.cif' withccfpath = no usecanonicalname = no \
         ccfpath = '.' recurse = no fileglob = '*.ccf|*.CCF' fullpath = no \
         withobservationdate = no observationdate = 'now' analysisdate = 'now'\
         category = 'XMMCCF' ignorecategory = no masterindex = no \
         withmasterindexset = no masterindexset = 'ccf.mif' append = no
```

The output of `cifbuild` is a file referred to as the Calibration Index File (CIF) (*ccf.cif* in the example above), created in the directory where `cifbuild` was run. We will refer to this directory from now onwards as */my_work*. This directory will contain all the files corresponding to the results of the analysis of a particular observation. It is thus recommended to run all subsequent SAS tasks from this directory. This directory could be any directory.

Once `cifbuild` has been executed, a new environment variable, `SAS_CCF`, has to be set to point to this file, *ccf.cif*, in order for SAS to know where to locate it:

```
export SAS_CCF=/my_work/ccf.cif [sh, bash, ksh]

setenv SAS_CCF /my_work/ccf.cif [csh, tcsh]
```

2.3.4 odfingest

The next step in setting up the basic SAS environment is to extract information from the instrument housekeeping files and from the calibration database and incorporate this information to what is referred to as the ODF summary file. This task is done through the SAS command `odfingest`, resulting in an extended SAS summary file needed for subsequent data processing. The task `odfingest` is run without additional parameters and the resulting file will be produced in the directory from which is run (*/my_work*), and named as:

```
'REV'_'OBS'_SCX00000SUM.SAS
```

where *REV* is the revolution number and *OBS* is the observation identification number.

The ODF summary file is an ASCII file. It contains all the necessary information that SAS needs to process the observation, including the path to the ODF files (changing the location of the ODF files after the `odfingest` task has run makes necessary to run the `odfingest` command again). Once the ODF summary file has been produced, SAS needs to know its location. For that, the `SAS_ODF` environment variable needs to be re-pointed to the newly created ODF summary file:

```
export SAS_ODF=/my_work/'REV'_'OBS'_SCX00000SUM.SAS [sh, bash, ksh]

setenv SAS_ODF /my_work/'REV'_'OBS'_SCX00000SUM.SAS [csh, tcsh]
```

where it is important to include the full path and file name of the ODF summary file.

The configuration setting, as described above, is the recommended one, where a working directory is created per observation, and where all the SAS analysis products will be located (unless explicitly stated differently). At this point, the working directory should have two files: the calibration index file and the ODF summary file.

All the steps listed above could be summarized in a setup script that could be called the first time one works on a particular dataset. The following is an example of such a script (csh/tcsh shell), where the path of the directory containing the ODF is the only input parameter $1. It is assumed that the script will be ran from the working directory */my_work*:

```
source /top_dir/xmmsas_YYYYMMDD_HHMM/setsas.csh
setenv SAS_ODF $1
setenv SAS_CCFPATH /path/to/repository/CCF
cifbuild
setenv SAS_CCF $PWD/ccf.cif
odfingest
set sumfile=`ls -1 *SUM.SAS`
setenv SAS_ODF $PWD/$sumfile
```

For further information, a SAS Start-Up thread guides you on how to initialize SAS as it has just been described.

2.4 Running SAS

There are currently three independent ways of operating SAS:

- Using the command line, as discussed in § 2.6.
- Using the SAS Graphical User Interface (GUI), as discussed in detail in § 3.
- From a Python session which can be started either from the command line or from a notebook, as dicussed in detail in § 2.9.

Starting with v.19, SAS includes a new infrastructure in Python which allows the execution of any SAS task either based on Python or not, from a pure Python session. Such interface aims at providing users with a bridge between SAS and Python, where a large amount of packages and tools are available from the user's community which might help in the process of analyzing XMM-Newton data. Simultaneously, new SAS Python-based tasks have been added which can be run from the command line, as any other SAS task.

SAS's main GUI can be accessed by typing `sas` on the command line. Also, almost every SAS task has its own specific GUI, which can be individually started by typing `task_name -d`.

Each type of interface has its own advantages and disadvantages, depending on the type of work the user has to do and the level of proficiency with SAS.

Intensive interactive work on single datasets could be done more efficiently using the GUI.

Beginners may find that the GUI is a good starting point since it allows to access and manage easily tasks with large number of parameters.

The Python interface, specially Jupyter Notebooks, could be preferible for users who are familiar with Python and want to work with SAS from there.

For the processing of large amounts of data, SAS tasks can be called from scripts written in any shell language –*bash, tcsh, ksh*– or using Python or Perl, with considerable efficiency.

2.5 Selecting a SAS task

To get a list of all the SAS tasks, start the main SAS GUI by typing the command `sas` on the command line. A particular SAS task GUI can simply be invoked by double-clicking on its name on the provided list. The use of the SAS GUI is explained in § 3. The SAS tasks can be grouped by:

- General utility tasks, which use both raw event files and calibrated event files
- Calibration tasks, which, for example, interact with the current calibration files
- Pipeline processing tasks
- EPIC specific tasks
- RGS specific tasks
- OM specific tasks

A list of packages in alphabetical order or classified by group is available at:

`http://xmm-tools.cosmos.esa.int/external/sas/current/doc/`

For detailed descriptions of individual tasks, the user is referred to the SAS package descriptions which can be accessed at the above address or via the SAS GUI help button. As a starting point, the user can read the package documentation of the list of frequently used tasks provided in Table 1.

Table 1: Some frequently used SAS tasks.

Task name	**Task description**
`arfgen`	Generates an EPIC ancillary response file
`calview`	An interactive viewer of the XMM-Newton calibration database
`cifbuild`	Creates a Calibration Index File for a given observation date
`edetect_chain`	EPIC source detection metatask
`emproc`	Fully configurable ”pipeline” processing of EPIC MOS observation data files (ODFs)
`epproc`	Fully configurable ”pipeline” processing of EPIC PN ODFs
`evselect`	Filters event lists and extracts images, spectra, time series and histograms
`odfbrowser`	Interactive graphical viewer of an XMM-Newton observation
`odfingest`	Prepares an ODF for processing
`omichain`	Fully configurable ”pipeline” processing of the OM imaging mode ODFs
`omfchain`	Fully configurable ”pipeline” processing of the OM fast mode ODFs
`omgchain`	Fully configurable ”pipeline” processing of the OM grism mode ODFs
`rgsproc`	Fully configurable ”pipeline” processing of the RGS part of an observation
`rgsrmfgen`	Constructs an RGS response matrix file
`rmfgen`	Generates an EPIC response file
`sas`	Launch the SAS graphical user interface
`srcdisplay`	Display image overlayed with positions of detected sources
`xmmselect`	Interactive filtering and extraction of images, spectra, time series and histograms

2.6 Running a SAS task from the command line

Each SAS task has its own command-line help that can be invoked by typing its name on the command line followed by the option *-h*. For example:

```
evselect -h
```

Individual tasks can be called using a set of parameters, which are entered on the command line. Every task has a Parameter Specification File which defines the name and type of each parameter and default values or allowed ranges. These parameters can also be accessed using the SAS GUI. The GUI reads the parameter specification file and provides a dialog window into which the user can enter values. The GUI then launches the task by generating a command line which can then be read in the *sas_log* file. The task parameter handling system (see: `http://xmm-tools.cosmos.esa.int/external/sas/current/doc/param/`), in addition to setting default values, is capable of handling complex expressions. Even further, some parameters can have *child parameters*, which are activated depending on the value of the *parent parameter*. For example:

```
evselect --xcolumn=RAWX
```

implies

```
--withimageset=yes
```

unless `--withimageset=no` is explicitly set.

All SAS tasks support the following command line options:

- `-h` provides information about the command line options
- `-d` launches the GUI for this specific task
- `-p` prints all parameters with their default and current value
- `-t` turns on tracing information from the libraries
- `-m` displays the HTML documentation of the task using a browser
- `-c` no clobber prevents files to be overwritten
- `-v` prints the version number of the task
- `-V` *opt* sets the verbosity level of the task to *opt*. The *opt* value ranges from 0 to 10 and the larger the verbosity value, the more log messages will be produced. The default value is 1, a value of 4 is recommended for a good verbose control. Larger values are only recommended for debugging purposes.
- `-w` *opt* suppresses warning messages. If no *opt* is given all warnings are suppressed. Multiple options can be given, *e.g.*: `-w` *10* `-w` *NoAttitudeData* `-w` *LowDisk* will suppress all warnings with code *NoAttitudeData* and *LowDisk* and shows only the first 10 of all other warnings.

- `-param=`*value* set the value of param to *value*

If the task uses the ODF Access Layer (OAL), the command line option `-odf` *odf* or `-o` *odf* is recognized as well. It specifies the ODF that is to be accessed by the OAL. The variable *odf* can be the name of an ODF summary file, as created by the task `odfingest`, or merely the name of a directory containing one. In the latter case, the summary file is assumed to have a name ending in **SUM.SAS*.

If the task uses the Calibration Access Layer (CAL), the following command line options are recognized:

- `-ccf` *cifname* or `-i` *cifname*:

  cifname is the name of a data set comprising a table with the name `CALINDEX`. This will normally be a CIF created by the task `cifbuild` (see § 2.3.3). *cifname* can also be the name of a directory. In this case the `CALINDEX` table is sought in a data set with the default name *ccf.cif* in the specified directory.

- `-ccffiles f1 ...` or `-f f1 ...`

  Blanks, commas, or colons separated list of CCF constituents replace the corresponding ones in the CCF pointed at via the `-ccf` command line option or the environment variable `SAS_CCF` (see below). Each specified file must be a valid CCF constituent.

- `-ccfpath dir1[:dir2 ...` or `-a dir1[:dir2 ... ]`

  A list of directories separated by commas that defines a search path along which CCF constituents are to be sought. If a CCF replacement file is passed via `-ccffiles` with its full absolute path, any specified search path is not considered in trying to access this constituent.

2.7 General settings affecting all SAS tasks

On a given SAS session, the SAS environment variables define the way in which SAS commands are executed. Several of these environment variables are part of the SAS initialization (*e.g.* `SAS_DIR` and `SAS_PATH`), others are optional.

The following is a description of some of the most useful environment variables in SAS:

- `SAS_DIR` is the top-level directory where SAS is installed.
- `SAS_CCFPATH` points to a list of colon separated directories where the CCF constituents are to be sought.
- `SAS_ODF` points to a SAS summary file (**SUM.SAS*, see § 2.3.4). Alternatively, it can point to a directory containing an ODF. If a name is specified via -o and `SAS_ODF` is defined, the former takes precedence over the latter. This environment variable is only relevant to tasks making use of the OAL.
- `SAS_CCF` points to the calibration index file (see § 2.3.3). If a value is provided via the command line option -i from any SAS task (see § 2.6) this takes precedence over any environment specification.

- `SAS_MEMORY_MODEL` determines how the internal memory is used by the data access (through the Data Access Layer (DAL)). There are basically two options for the memory model: High Memory (*high*) and HighLow Memory (*highlow or low*) model. In the *high* model every time a dataset is opened it is kept entirely in memory and all subsequent operations are performed on the memory-loaded dataset. In the *low* model the data is loaded into memory only when their access is needed (when opening a dataset only their attributes are kept in memory). While the *high* model should bring higher performance, its use implies normally a high memory consumption, which can lead to swapping, producing a poorer performance. Therefore for machines with less than about 1GB RAM it is recommended to use the *low* model. The default value for `SAS_MEMORY_MODEL` is *high*.

- `SAS_VERBOSITY` determines the debug level of the task. The value ranges from 0 to 10 with increasing verbosity level. The default value is 1, a value of 4 is recommended for getting a very communicative SAS, larger values should only be used for debugging purposes.

- `SAS_SUPPRESS_WARNING` determines whether warning messages produced during the execution of any given task are displayed or not. It is a boolean which means any value not equal to 0 sets it to true. By default is set to true.

- `SAS_BROWSER` specifies the browser to be launched when any SAS task is invoked with the -m command line option, to display the HTML documentation on such task. It could be specified either as the absolute path to the browser binary (e.g. /usr/bin/firefox) or just simply the browser name. For that latter, the browser binary must be accessible through the $PATH variable.

The SAS tasks produce error messages at levels called *message*, *warning*, *error* and *fatal*.

- At *message* level, a message is reported to the user and processing continues.

- At *warning* level, a warning message is reported to the user and processing continues.

- At *error* level, an error message is reported and the current operation is aborted. Control may return to the calling programme which can take an appropriate action.

- At *fatal* level, a fatal error is reported to the user and all processing is aborted. A fatal error is generated if the internal state of the programme is disrupted, for example if an invalid value is found in a variable.

Error messages are characterized by a layer and a verbosity level. The layer indicates the layer in the system where the message is coming from (*e.g.* application, user interface, application library or system library). The verbosity level determines whether or not the message will be reported. The user can specify the verbosity level. If the verbosity of a message is large enough compared to the system verbosity level, the message will be reported. The verbosity level differs for the different layers.

2.8 SAS input and output files

The SAS tasks processes input and output data in the form of datasets. These are usually saved on disk as FITS files.

FITS files have a primary header, a primary image array and optional extensions, each with a header. In the case of the XMM-Newton FITS files, the primary header contains information about the mission, the instrument, the observation mode, the investigator, the target coordinates, the observation date and initial processing information. In all FITS headers, the information is in the form of keywords with assigned values.

It is important to note that the naming convention of XMM-Newton files is slightly different from that historically used for FITS files. Table 2 provides a handy *conversion table* between the two nomenclatures.

FITS name	**XMM-Newton dataset name**
Header	Header
Primary Header Data Units/Array	First Data Block/Primary Array
Extension	Data block
Image	Array
Binary Table	Table
Keyword	Attribute
Column/Rows	Column/Rows

Table 2: *Conversion table* between FITS and XMM-Newton dataset constituents naming convention.

2.9 Running SAS from Python

Besides new Python-based tasks which can be used from the command line, SAS includes now a Python core infrastructure, known as `pysas`, which allows the use of all SAS tasks from a Python session, either running it from the command line using *ipython* or from a web browser using the *Jupyter notebook*. Such methods, allow users to perform the whole processing of XMM-Newton data completely within Python.

Prior to starting a Python session to work with SAS, the basic SAS environment must be initialised as indicated in § 2.3.1 and the *SAS_CCFPATH* must be set to the directory which stores all CCFs.

The SAS Python package `pysas` includes a module named *wrapper* which must be imported into the Python session as follows,

```
from pysas.wrapper import Wrapper as w
```

where *w* is an alias for the object *Wrapper*, which can be used from now onwards to run any SAS task by making a specific instance of such object.

To get started, the Python task `sasver`, provides a sort of about SAS, as an example on how to run any other SAS task.

As seen in § 2.6, every SAS taks can be called using a specific set of parameters and options which can be passed to it through the command line. The equivalent way to do this from a Python session, is through the use of a Python list. Let *inargs* be the name of such list. To pass the option *–version* to the `sasver` task, one must fill in *inargs* with such options, as follows,

```
inargs = ['--version']
```

To run the task, create an instance of the generic object *w*, with the options defined in *inargs*. This is done as follows,

```
t = w('sasver', inargs)
```

In Python terms, *t* is known as an 'instantiation' of object *Wrapper* or, equivalently, its alias *w*.

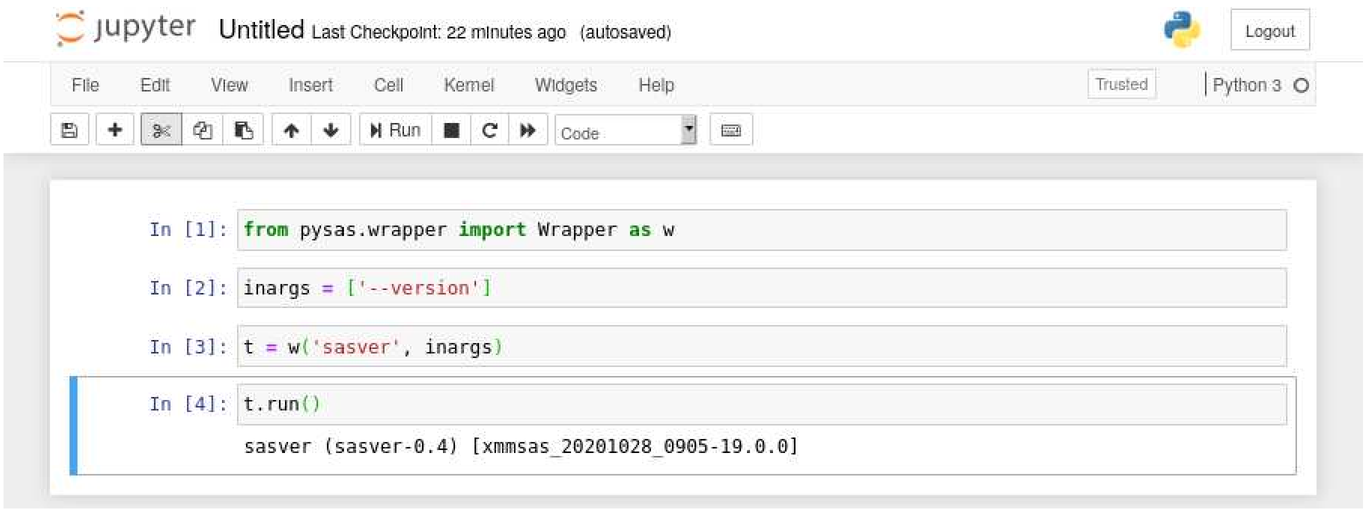
Now, the task `sasver` can be run as follows,

```
t.run()
```

which should produce, in this case, the following output:

```
sasver (sasver-0.4) [xmmsas_20201028_0905-19.0.0]
```

Figure § 1 shows the previous sequence of commands as executed from a Jupyter notebook. The figure shows four consecutive notebook cells whose inputs are indicated by *In [n]:* where *n* are consecutives integer numbers *1, 2, 3, 4, ...* The line immediately after the cell beginning with *In [4]:* shows the output generated by the command entered on this last cell.



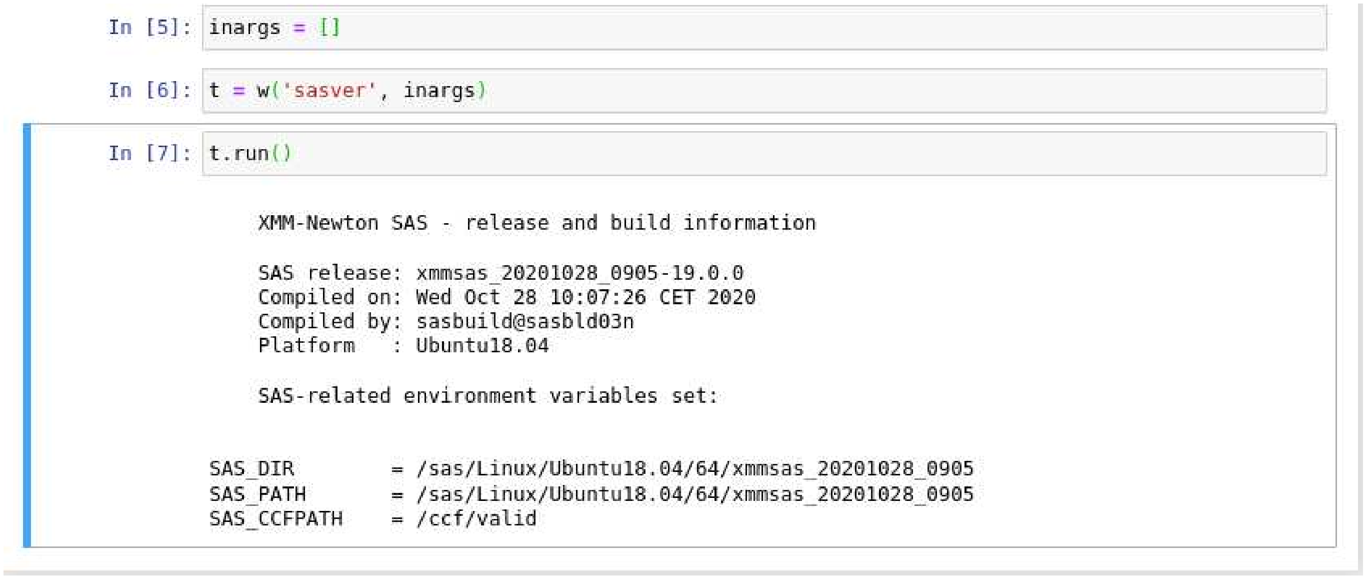
```
In [1]: from pysas.wrapper import Wrapper as w

In [2]: inargs = ['--version']

In [3]: t = w('sasver', inargs)

In [4]: t.run()
        sasver (sasver-0.4) [xmmsas_20201028_0905-19.0.0]
```

Figure 1: Starting a Python session from a Jupyter notebook.

Similar sequences of commands could be used to make more ellaborated commands. For example, Figure § 2 shows the execution of task `sasver` without arguments, using *inargs = []* and Figure § 3 shows the execution of another Python task named `startsas` using as arguments *inargs =*

['-h']. This option produces some help information, including a list of available options and a table displaying all available parameters, in this case for `startsas`.

Figure § 4 shows in its last notebook cell how the previous three commands could be condensed in a single one.

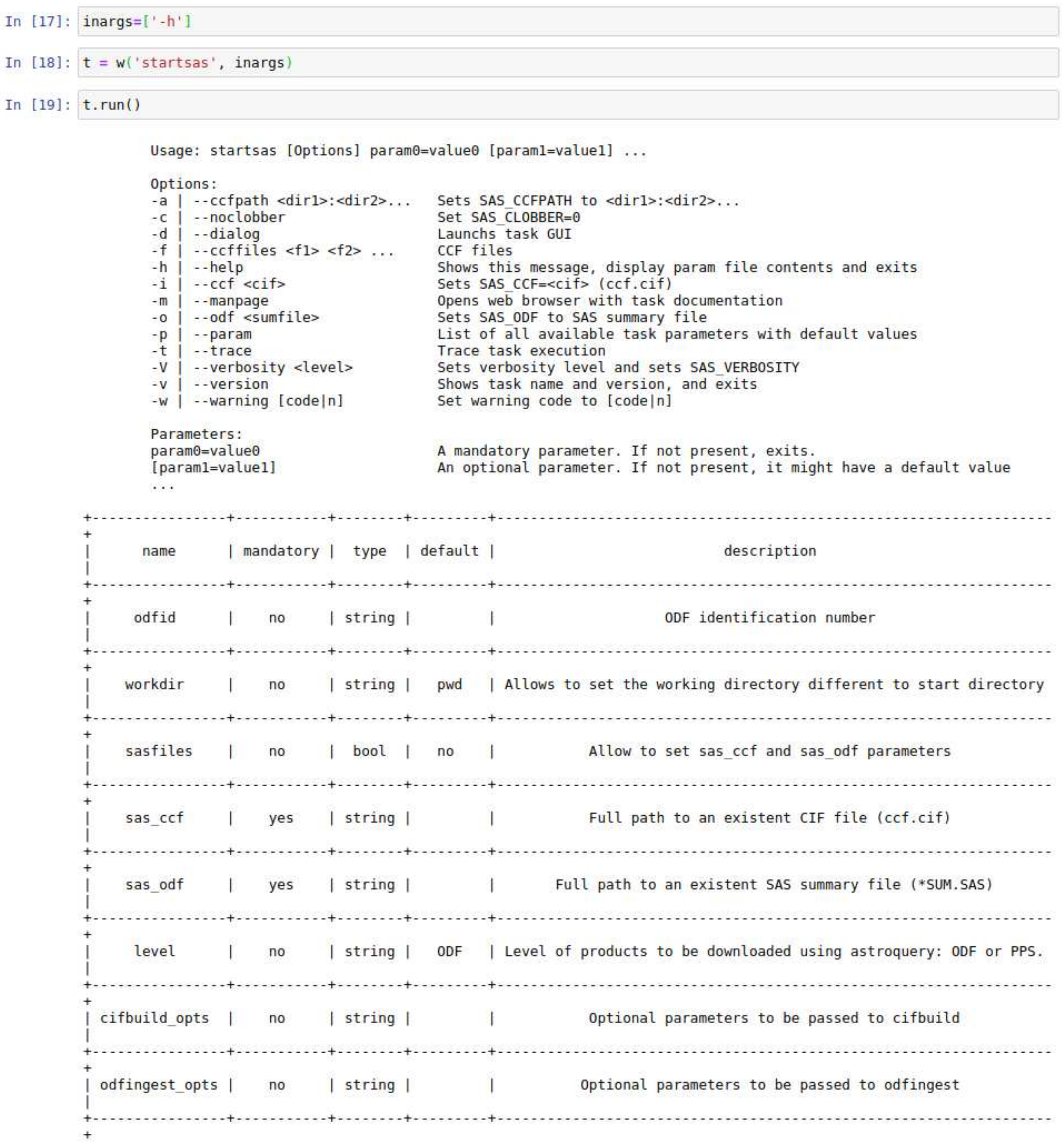


```
In [5]: inargs = []

In [6]: t = w('sasver', inargs)

In [7]: t.run()

            XMM-Newton SAS - release and build information

            SAS release: xmmsas_20201028_0905-19.0.0
            Compiled on: Wed Oct 28 10:07:26 CET 2020
            Compiled by: sasbuild@sasbld03n
            Platform   : Ubuntu18.04

            SAS-related environment variables set:


        SAS_DIR          = /sas/Linux/Ubuntu18.04/64/xmmsas_20201028_0905
        SAS_PATH         = /sas/Linux/Ubuntu18.04/64/xmmsas_20201028_0905
        SAS_CCFPATH      = /ccf/valid
```

Figure 2: Execution of the SAS command `sasver`.

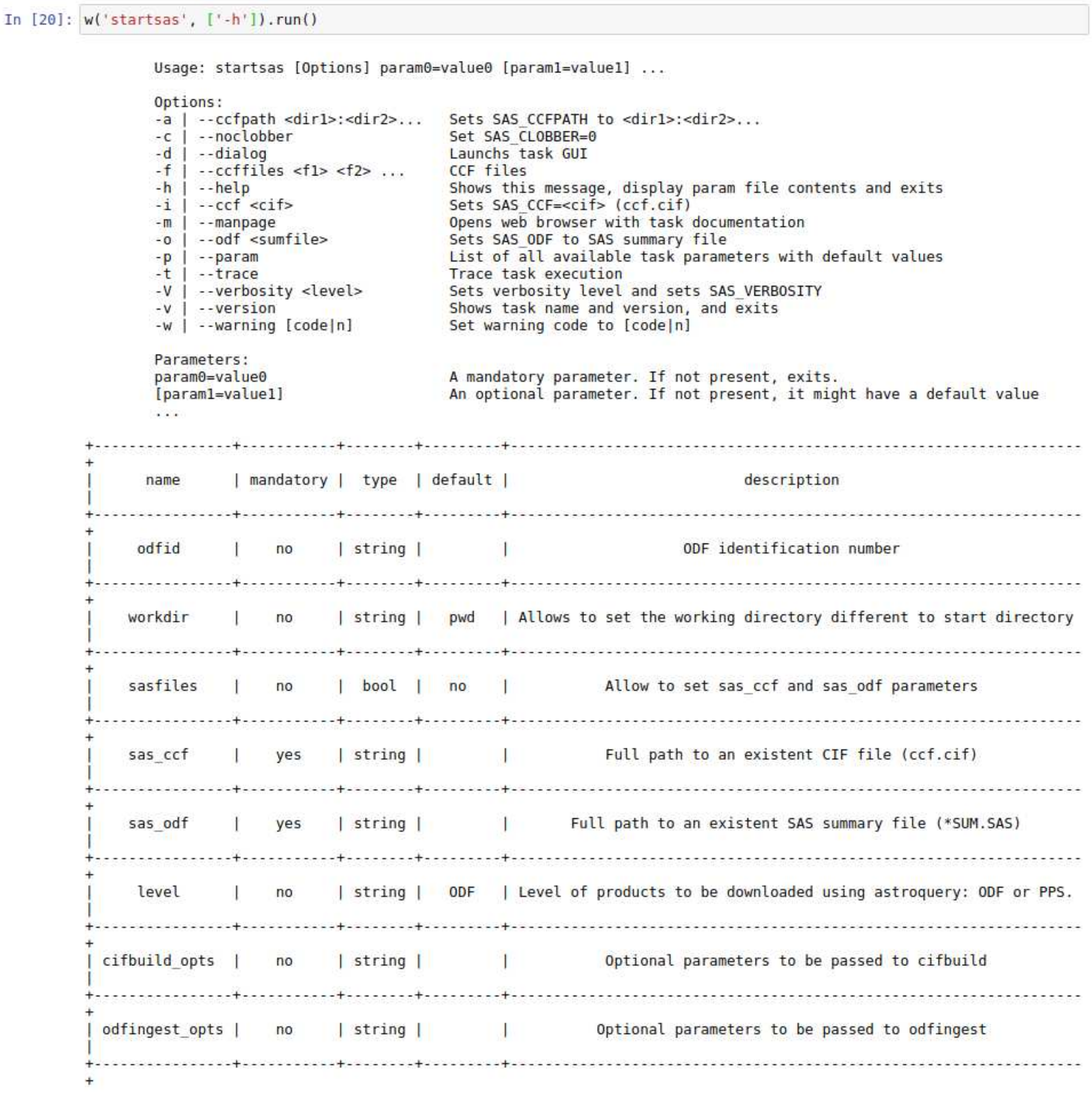
The task `startsas` can be used to start working with SAS. This is done by using the task paramater *odfid* to set the ID of the XMM-Newton observation of interest. The task will download such observation using the *astroquery* Python module and will run the SAS tasks *cifbuild* and *odfingest* to obtain the CIF and observation summary files. Figure § 4 shows all the available parameters that can be used with `startsas`. Notice that these paramaters can be used as well when running `startsas` from the command line.

For further information, a Start-up SAS Analysis Threads in Python guides you on how to begin using the Python interface to SAS and the different `startsas` funcionalities.



```
In [17]: inargs=['-h']

In [18]: t = w('startsas', inargs)

In [19]: t.run()

        Usage: startsas [Options] param0=value0 [param1=value1] ...

        Options:
        -a | --ccfpath <dir1>:<dir2>...   Sets SAS_CCFPATH to <dir1>:<dir2>...
        -c | --noclobber                  Set SAS_CLOBBER=0
        -d | --dialog                     Launchs task GUI
        -f | --ccffiles <f1> <f2> ...     CCF files
        -h | --help                       Shows this message, display param file contents and exits
        -i | --ccf <cif>                  Sets SAS_CCF=<cif> (ccf.cif)
        -m | --manpage                    Opens web browser with task documentation
        -o | --odf <sumfile>              Sets SAS_ODF to SAS summary file
        -p | --param                      List of all available task parameters with default values
        -t | --trace                      Trace task execution
        -V | --verbosity <level>          Sets verbosity level and sets SAS_VERBOSITY
        -v | --version                    Shows task name and version, and exits
        -w | --warning [code|n]           Set warning code to [code|n]

        Parameters:
        param0=value0                     A mandatory parameter. If not present, exits.
        [param1=value1]                   An optional parameter. If not present, it might have a default value
        ...

+----------------+-----------+--------+---------+-----------------------------------------------------------------
+
|      name      | mandatory |  type  | default |                            description
|
+----------------+-----------+--------+---------+-----------------------------------------------------------------
+
|     odfid      |    no     | string |         |                     ODF identification number
|
+----------------+-----------+--------+---------+-----------------------------------------------------------------
+
|    workdir     |    no     | string |   pwd   | Allows to set the working directory different to start directory
|
+----------------+-----------+--------+---------+-----------------------------------------------------------------
+
|    sasfiles    |    no     |  bool  |   no    |           Allow to set sas_ccf and sas_odf parameters
|
+----------------+-----------+--------+---------+-----------------------------------------------------------------
+
|    sas_ccf     |    yes    | string |         |           Full path to an existent CIF file (ccf.cif)
|
+----------------+-----------+--------+---------+-----------------------------------------------------------------
+
|    sas_odf     |    yes    | string |         |       Full path to an existent SAS summary file (*SUM.SAS)
|
+----------------+-----------+--------+---------+-----------------------------------------------------------------
+
|     level      |    no     | string |   ODF   | Level of products to be downloaded using astroquery: ODF or PPS.
|
+----------------+-----------+--------+---------+-----------------------------------------------------------------
+
| cifbuild_opts  |    no     | string |         |           Optional parameters to be passed to cifbuild
|
+----------------+-----------+--------+---------+-----------------------------------------------------------------
+
| odfingest_opts |    no     | string |         |          Optional parameters to be passed to odfingest
|
+----------------+-----------+--------+---------+-----------------------------------------------------------------
+
```

Figure 3: Execution of the SAS command *startsas -h*.



```
In [20]: w('startsas', ['-h']).run()
```

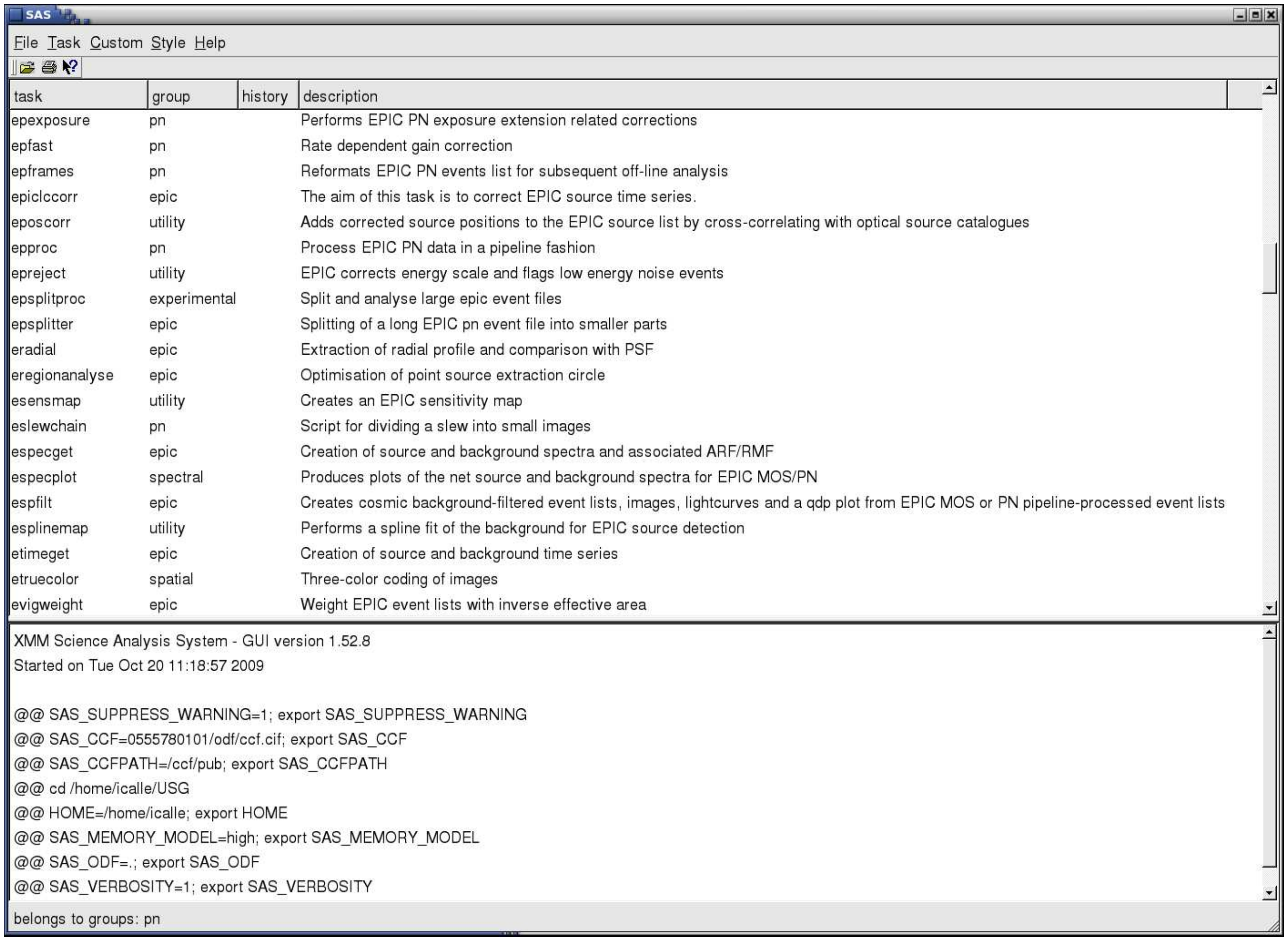
```
        Usage: startsas [Options] param0=value0 [param1=value1] ...

        Options:
        -a | --ccfpath <dir1>:<dir2>...   Sets SAS_CCFPATH to <dir1>:<dir2>...
        -c | --noclobber                  Set SAS_CLOBBER=0
        -d | --dialog                     Launchs task GUI
        -f | --ccffiles <f1> <f2> ...     CCF files
        -h | --help                       Shows this message, display param file contents and exits
        -i | --ccf <cif>                  Sets SAS_CCF=<cif> (ccf.cif)
        -m | --manpage                    Opens web browser with task documentation
        -o | --odf <sumfile>              Sets SAS_ODF to SAS summary file
        -p | --param                      List of all available task parameters with default values
        -t | --trace                      Trace task execution
        -V | --verbosity <level>          Sets verbosity level and sets SAS_VERBOSITY
        -v | --version                    Shows task name and version, and exits
        -w | --warning [code|n]           Set warning code to [code|n]

        Parameters:
        param0=value0                     A mandatory parameter. If not present, exits.
        [param1=value1]                   An optional parameter. If not present, it might have a default value
        ...

+----------------+-----------+--------+---------+-------------------------------------------------------------------
+
|      name      | mandatory |  type  | default |                            description
|
+----------------+-----------+--------+---------+-------------------------------------------------------------------
+
|     odfid      |     no    | string |         |                       ODF identification number
|
+----------------+-----------+--------+---------+-------------------------------------------------------------------
+
|    workdir     |     no    | string |   pwd   | Allows to set the working directory different to start directory
|
+----------------+-----------+--------+---------+-------------------------------------------------------------------
+
|    sasfiles    |     no    |  bool  |   no    |            Allow to set sas_ccf and sas_odf parameters
|
+----------------+-----------+--------+---------+-------------------------------------------------------------------
+
|    sas_ccf     |    yes    | string |         |            Full path to an existent CIF file (ccf.cif)
|
+----------------+-----------+--------+---------+-------------------------------------------------------------------
+
|    sas_odf     |    yes    | string |         |       Full path to an existent SAS summary file (*SUM.SAS)
|
+----------------+-----------+--------+---------+-------------------------------------------------------------------
+
|     level      |     no    | string |   ODF   | Level of products to be downloaded using astroquery: ODF or PPS.
|
+----------------+-----------+--------+---------+-------------------------------------------------------------------
+
| cifbuild_opts  |     no    | string |         |            Optional parameters to be passed to cifbuild
|
+----------------+-----------+--------+---------+-------------------------------------------------------------------
+
| odfingest_opts |     no    | string |         |           Optional parameters to be passed to odfingest
|
+----------------+-----------+--------+---------+-------------------------------------------------------------------
+
```

Figure 4: Execution of the SAS command *startsas -h* on a single cell.

3 SAS graphical user interface

3.1 Getting started

The SAS GUI provides an easy way of running tasks without having to memorize commands. The GUI is specially intended for interactive analysis of XMM-Newton data, and can be started by typing `sas` on the command line. This should display a main window similar to the one shown on figure 5.



task	group	history	description
epexposure	pn		Performs EPIC PN exposure extension related corrections
epfast	pn		Rate dependent gain correction
epframes	pn		Reformats EPIC PN events list for subsequent off-line analysis
epiclccorr	epic		The aim of this task is to correct EPIC source time series.
eposcorr	utility		Adds corrected source positions to the EPIC source list by cross-correlating with optical source catalogues
epproc	pn		Process EPIC PN data in a pipeline fashion
epreject	utility		EPIC corrects energy scale and flags low energy noise events
epsplitproc	experimental		Split and analyse large epic event files
epsplitter	epic		Splitting of a long EPIC pn event file into smaller parts
eradial	epic		Extraction of radial profile and comparison with PSF
eregionanalyse	epic		Optimisation of point source extraction circle
esensmap	utility		Creates an EPIC sensitivity map
eslewchain	pn		Script for dividing a slew into small images
especget	epic		Creation of source and background spectra and associated ARF/RMF
especplot	spectral		Produces plots of the net source and background spectra for EPIC MOS/PN
espfilt	epic		Creates cosmic background-filtered event lists, images, lightcurves and a qdp plot from EPIC MOS or PN pipeline-processed event lists
esplinemap	utility		Performs a spline fit of the background for EPIC source detection
etimeget	epic		Creation of source and background time series
etruecolor	spatial		Three-color coding of images
evigweight	epic		Weight EPIC event lists with inverse effective area

```
XMM Science Analysis System - GUI version 1.52.8
Started on Tue Oct 20 11:18:57 2009

@@ SAS_SUPPRESS_WARNING=1; export SAS_SUPPRESS_WARNING
@@ SAS_CCF=0555780101/odf/ccf.cif; export SAS_CCF
@@ SAS_CCFPATH=/ccf/pub; export SAS_CCFPATH
@@ cd /home/icalle/USG
@@ HOME=/home/icalle; export HOME
@@ SAS_MEMORY_MODEL=high; export SAS_MEMORY_MODEL
@@ SAS_ODF=.; export SAS_ODF
@@ SAS_VERBOSITY=1; export SAS_VERBOSITY
```

belongs to groups: pn

Figure 5: SAS Graphical User Interface window.

The upper half of the window is what is called task browser, which allows the user to select and run tasks. The lower half of the window is called log panel, and is used to show messages when the selected task is ran, including warnings and error messages. At the very bottom of the window is a *message panel* which shows transient messages.

3.2 A quick tour

1. **Preconfigure the SAS session**

Although most of the settings can be created / modified within a SAS session, it is recommended to start SAS with all environment variables already defined, *e.g.* via a startup script as described under § 2.3.

2. **Start SAS**

   It is convenient to create a directory to run SAS and hold the processed results:

   ```
   mkdir my_work
   cd my_work
   sas &
   ```

   The command `sas` launches the main SAS GUI.

3. **Preferences: (Re-)Configure CCF and ODF directories, verbosity level and memory model**

   Using the preferences dialog in the file Menu of the GUI it is possible to set or reset the environment variables pointing to: the ODF Summary file or directory, the CCF index file, the directory(ies) containing the calibration files and the working directory. In addition the **verbosity** level (determining the debugging level of the tasks, 0=low, 10=maximum) can be set as well as the **memory model** to be used (see § 2.7).

4. **Select a task**

   The upper half of the main window is the task browser. One can click on the column headings to sort the tasks in various ways. Double-click on any given task to access the specific GUI of that task and configure its parameters.

5. **Configure parameters**

   The parameter dialog (see section 3.5) allows to configure the parameters of a task before running it.

   If the task requires input data, they can be selected by opening a dataset browser (see section 3.7). This allows to browse through the file hierarchy and select SAS datasets or individual components, such as tables, arrays or columns.

6. **Press the Run button**

   When the parameters of a given task have been configured, by pressing the ”Run” button the task is executed. It is possible to kill a task (see section 3.6) from the Task menu.

7. **Examine the log**

   The lower half of the main GUI window is a log panel (see section 3.8) which displays messages from the task. Check that the task ran successfully by looking for warnings or error messages (see section 3.9) displayed in the log panel (see section 3.8).

8. **Run another task**

   The results from running a task will be output into the current directory, unless a different path has been specified for the output files. These files will typically form the input to the next task when running a sequence of processing steps.

It is possible to create a queue of tasks that will be executed when the current task finishes (see § 3.6) and to define the parameters for subsequent tasks before the current task has finished.

9. **Save or print the log**

   When the processing session is finished, the log (see section 3.8) provides a record of the steps that have been carried out, with all the parameters and any messages received from the tasks. This log can be saved for future reference. Scripts can also be constructed from those single calls.

   The log is automatically saved in the file `sas_log` in the current directory. It can also be printed out from the "File" menu or *tool bar*.

   The environment variable `SAS_SUPPRESS_WARNING` (by default set to a value of 1 in the SAS initialization) sets the maximum number of occurrences a specific warning shall appear in the log (and in the corresponding warning windows if ran from the GUI). If set to a value of 0, only the summary for each warning will be written to the log instead. In all cases a summary line specifying the number of occurrences for each issued warning is written to the log file.

10. **Obtaining help**

    The SAS GUI provides yellow *tool tips* which pop up when the cursor is placed over an item. To activate this functionality, first select the '?' button and then click on a specific task. Also, the main window has a *Help tool*, displayed as 'Help' in the top tool bar. Select a task and then go to the Help tool and select 'Task' to obtain more detailed help. Finally, the Help menu provides access to the on-line documentation. See section 3.10 for further details.

3.3 Selecting an ODF

At the start of a SAS session, the environment variable `SAS_ODF` should point to either the directory containing the ODF files, or to the ODF Summary File (as explained under § 2.3). This can be done from the SAS GUI by choosing "Preferences" from the "File" menu, where a dialog box pops up. Using this dialog box, the path of an ODF directory or the name of the ODF Summary File can be defined.

The ODF directory can be specified either by giving the absolute path (starting with "/") or by giving a path relative to the directory in which the SAS GUI was started. The "Folder" button pops up a dataset browser (see section 3.7) which allows to search for the directory and select it.

It is possible to select a different ODF directory at any time during the session. Any tasks ran subsequently will use the new ODF.

3.4 Task browser

The upper half of the main window is called the *Task Browser*, and is used to select and run SAS tasks.

Double clicking on a task causes the corresponding parameter dialog (see section 3.5) window to pop-up so that parameters can be entered and the task started.

Clicking on any of the column headings sorts the list alphabetically on that field. Clicking again reverses the order. For example, clicking on the "group" heading groups all tasks by type and /or instrument.

When a task is selected by double clicking, a number appears in the "history" column. This number is incremented as successive tasks are run. Clicking on the "history" column heading sorts the list in the order in which the tasks were run (putting them in the bottom or the top of the list, depending if one or two clicks); this makes it easier to locate recently run tasks.

It is possible to locate a task quickly by typing the first few characters of its name. First click in the task browser, or use the 'Tab' key to select the browser. To locate another task, first click on another task to reset the search.

3.5 Parameter dialogs

Each task has an associated parameter dialog window. These individual task GUIs are used to enter the values of the different task parameters and to run the task. The parameter dialog windows are opened by double-clicking any of the tasks listed under the "task" column.

The following parameter dialog window (figure 6) illustrates some of the basic parameter types. Each parameter type has a corresponding widget type. For example, a boolean parameter is entered using a check-box (`withexposure`); a choice parameter is entered by using a pop-up menu that allows to select from a set of options (`sampling`); a filename parameter is entered as a string (`imagesets`), with the option of popping up a file browser by pressing the button with the folder icon (see § 3.7).

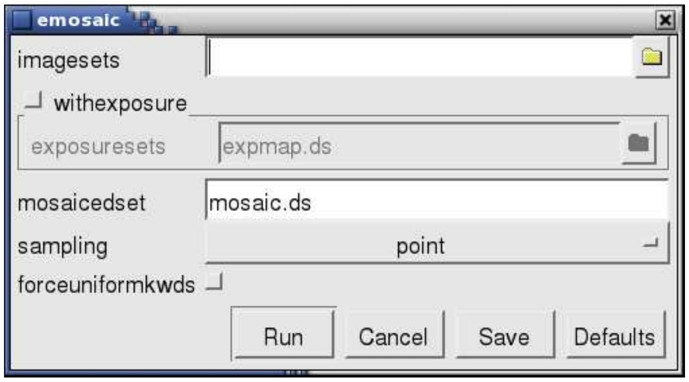


Figure 6: SAS parameter dialog window.

If the task has a large number of parameters, the dialog window may have scroll-bars. The scroll bars will disappear if the size of the dialog window is increased sufficiently.

Further information on a parameter can be obtained by placing the cursor over the parameter widget. This causes a yellow *tool-tip* to pop-up if the parameter file defines a *prompt* field for the parameter.

The parameter dialog has the following buttons:

Run	Run the task with the selected parameters
Cancel	Close the parameter dialog window without running the task or changing the parameters
Save	Saves the value of the parameters
Defaults	Reset the parameters to their default values

When a task has been run, the parameter values are retained until the next time that the task is run (within the same session). The *Defaults* button may be used to reset the parameters of a task to their default values. The ”Task” menu in the main SAS GUI provides an option ”Revert to defaults” to reset all the parameters of all the tasks to their defaults.

3.6 Task control

It is possible to kill a running task from the ”Task” menu. This is useful if a long task is accidentally started with the wrong parameters or if a task appears to ”hang” for some reason. Killing a task may, of course, result in the output files being truncated or corrupted.

For interactive processing, it is normal to run one task at a time. However, once a task has started, a parameter dialog can be opened to configure the parameters in preparation for running the next task. By pressing the ”Run” button before the previous task has finished, one gets the option of running the task immediately or queuing it for later execution:

- Immediate execution is appropriate if the tasks make use of separate files, so that they may be run in parallel.
- Queuing is appropriate to create a process chain, where each task makes use of the output from the previous task.

The next queued task is started automatically when all current running tasks have finished. Tasks are logged when they are started.

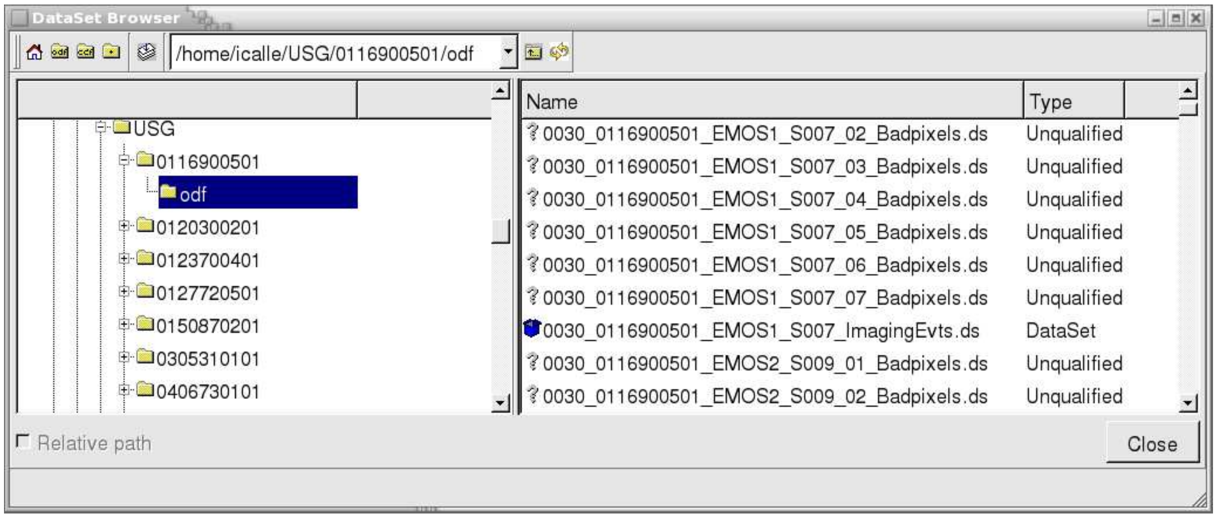
When a task is started, or queued for later execution, the parameter values are saved along with the task. Consequently, editing the parameters and queuing a second instance of a task will not affect the parameters of a task that is already running or queued.

The current implementation has the following limitations:

- Changing preferences which affect a task, such as the setting of ODF/CCF directories, will affect queued tasks which have not yet started.
- The ”kill” command on the ”Task” menu kills the last task started. It is only possible to kill an earlier task by killing all later tasks.
- The ”kill” command cannot be used to remove a queued task which has not yet started.
- If a queued task fails, the remaining tasks in the queue will still be executed.

3.7 Browsing a dataset

The *dataset browser* window is invoked from various widgets through the parameter dialog window. The *dataset browser* allows the selection of datasets and their component tables, columns and arrays (see figure 7). The browser can also be invoked from the ”File” menu or tool-bar, from the main SAS GUI, simply to inspect data without making a selection.



Name	Type
0030_0116900501_EMOS1_S007_02_Badpixels.ds	Unqualified
0030_0116900501_EMOS1_S007_03_Badpixels.ds	Unqualified
0030_0116900501_EMOS1_S007_04_Badpixels.ds	Unqualified
0030_0116900501_EMOS1_S007_05_Badpixels.ds	Unqualified
0030_0116900501_EMOS1_S007_06_Badpixels.ds	Unqualified
0030_0116900501_EMOS1_S007_07_Badpixels.ds	Unqualified
0030_0116900501_EMOS1_S007_ImagingEvts.ds	DataSet
0030_0116900501_EMOS2_S009_01_Badpixels.ds	Unqualified
0030_0116900501_EMOS2_S009_02_Badpixels.ds	Unqualified

Figure 7: SAS dataset browser window.

The left panel of the browser window shows a hierarchical view of the file system, extending from the root directory, through datasets to their component tables, arrays and columns. Items in the hierarchical view can be expanded by clicking in their ”Name” column. A +/− sign shows whether an item is collapsed or expanded. Clicking on an item in the ”Type” or ”Data” column will cause it to be highlighted, as indicated by a rectangle around the name. The right panel shows information on the highlighted item.

The right panel and the attribute page of the left panel are arranged in columns. The columns may be sorted in various ways, by clicking on the appropriate column heading. The panels can be resized with the small handle on the the divider line, which separates them.

Double-clicking on a data item (column or array) will divide the right panel in two showing further information. For a column, this is a scrolling view of the values; for an array, it currently just shows the size of the array.

When the browser is invoked from a parameter dialog window, the ”Select” column will show the items which may be selected. For example, a ”Column” parameter allows a column to be selected by clicking in the ”Select” column. A circle indicates that only one item may be selected, as with a ”radio button”; selecting one item deselects the others. A square indicates that multiple selection is possible, as with check-boxes; this is used for list parameter types (*e.g.* column-list). A ”...” in the ”Select” column indicates that a selected item is not visible because its container is collapsed.

When the browser is invoked from a parameter dialog window, it returns the selected items as the parameter value when the ”Ok” button is pressed. The ”Absolute path” check-box determines whether the parameter is specified using an absolute file path or a path relative to the current directory (in which the SAS was started). The ”Cancel” button may be used to close the browser without changing the previous parameter value. When the browser is invoked from the "File" menu of the main SAS GUI, the "Cancel" button and "Absolute path" check-box are not displayed, since they are not relevant.

At the top of the browser window are four buttons which can be used to quickly locate some commonly used directories. These are the user's home directory, the ODF directory, the CCF directory, and the current working directory from which the SAS GUI was started. The next button to the right is useful when selecting parameters for a task. Pressing this button will show or hide a window that lists all currently selected entries. The (non-editable) pull-down menu allows to quickly jump to a previous visited item. As of SAS 6.0, a new button was added for refreshing the contents of the selected directory. This allows to see files newly created during the working session.

3.8 Using the log

The lower part of the SAS GUI is a *log panel*, which records the commands that are used and displays messages that come up as a result of running the different tasks. Each time a task is executed from the GUI, an equivalent command-line is written to the log. These lines have the prefix "@@", so that they may be easily identified. The "File" menu has an option to extract the commands and save them into an executable script. It is possible to edit the script and replace file names or task arguments so that the script can be ran on different data.

The log also records warnings and error messages (see section 3.9) received from the task. These are prefixed with "**", so that they are clearly visible. Any other output from the tasks (those normally written to STDOUT) is logged without any prefix.

As well as being displayed in the SAS window, the log is also written to the file "sas_log" in the directory from which the GUI was invoked.

The log may not only be printed using the "Print log..." command from the "File" menu, but also saved as a script for further use by the "Save as script..." option in the same menu.

3.9 Errors and warnings

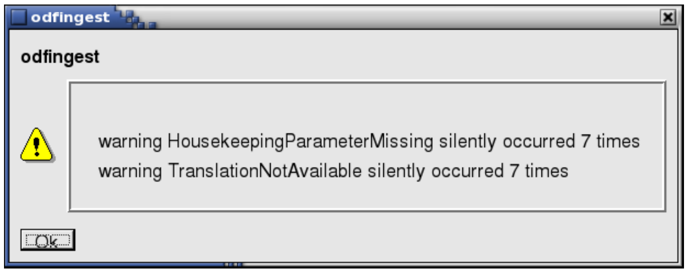
Tasks which are ran from the GUI can generate various error messages, warnings and information messages. These messages are written to the sas_log (see section 3.8) and may also pop up a dialog to alert the user.

Warning dialogs include a check-box which allow subsequent occurrences of the same warning to be ignored so that no further user interaction is needed. However, all occurrences are still written to the log. The warning is re-enabled next time the task is run.

3.10 Using on-line help

The SAS GUI provides 3 levels of help:

- Yellow *tool tips* pop up when the cursor is placed over an item.
- The main window has a *Help tool*, in the tool bar; select the help tool and click on an item to obtain more detailed help.



```
warning HousekeepingParameterMissing silently occurred 7 times
warning TranslationNotAvailable silently occurred 7 times
```

Figure 8: Example of SAS warning message window.

- The Help menu provides access to the on-line documentation (each SAS task is fully documented, its documentation tree including several different sections, like algorithm, input, output, parameters, etc).

The on-line documentation request will start a browser if it is not already running before selecting ”Help”. The help menu passes the URL of the SAS documentation to that browser.

3.11 Accessing calibration data

The XMM-Newton calibration database consists of calibration datasets forming the current calibration file (CCF) and of a number of calibration algorithms and access functions which constitute the calibration access layer (CAL). Many of the datasets in the CCF contain parameters that are meaningful only in conjunction with the calibration algorithms provided in the calibration access layer. The appropriate way to access the calibration data, either in raw form (the contents of the datasets themselves) or in the interpreted form (the output of the algorithms) is through the functional interface provided by the calibration access layer. The SAS task `calview` allows the user to visualize calibration quantities (also derived ones). The task is simply called by typing:

```
calview
```

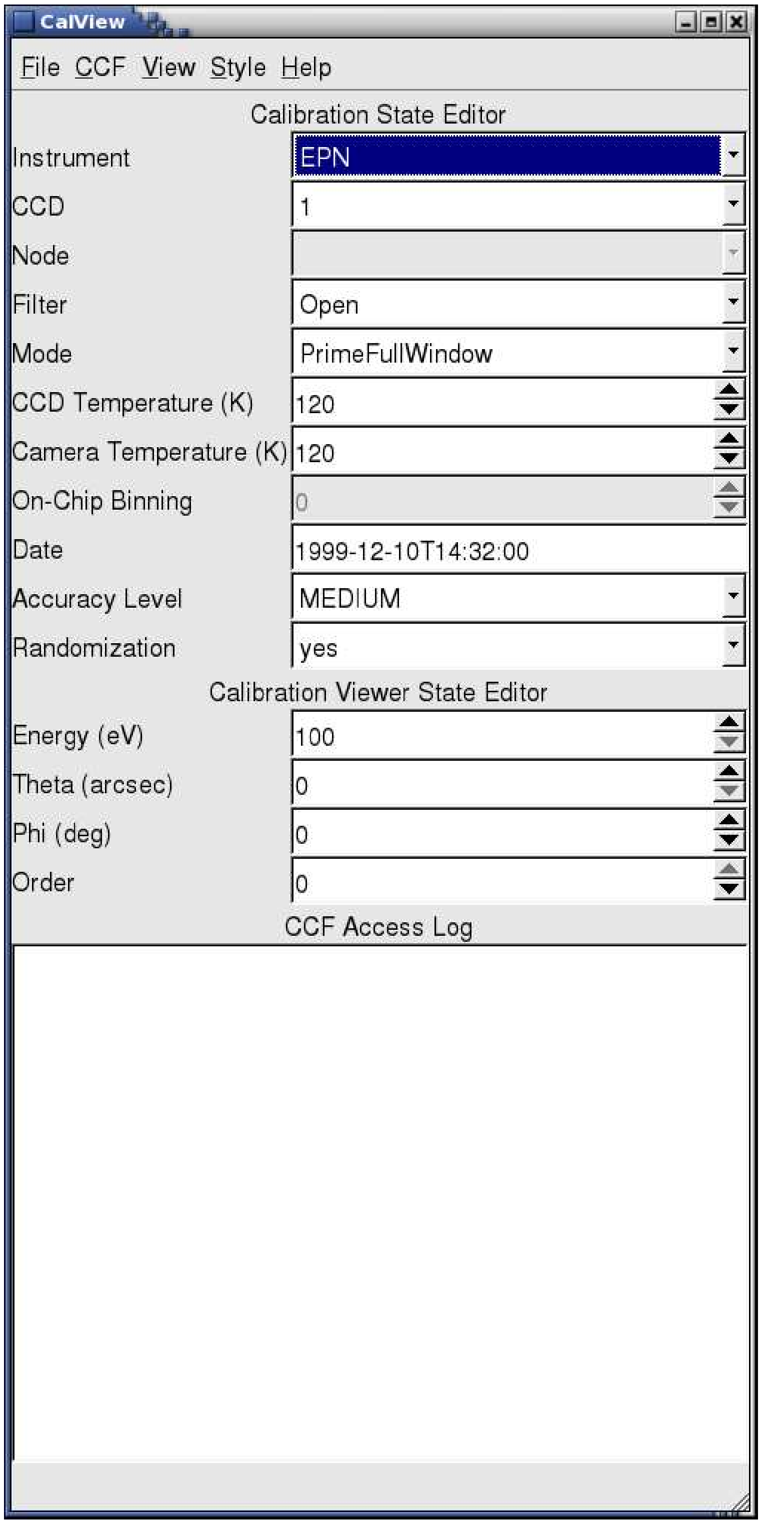
`calview` interacts with the CAL through the interfaces provided by the calibration state server. The calibration state server consists of a calibration state editor and a calibration viewer state editor (see figure 9). The calibration state server allows one to set any of the calibration state parameters. These are: instrument, ccd, node, filter and mode identifiers, ccd and camera temperatures, on-chip binning factor, date, accuracy level, and randomization. The top part of the `calview` widget panel can be used to edit the calibration state. Through the pull down menu labeled ”CCF” of `calview`, one can direct the cal to use a particular set of calibration datasets. It is possible to point the cal to a CCF directory, to a CCF index file (see the task `cifbuild` for information on how to generate one), or add individual CCF components to an existing list.

The calibration view server allows the user to edit a number of state variables that affect the display of the calibration output. The following variables can be set: energy, position in the field of view and spectral order. These variables serve as input data to the calibration algorithms. For instance, for a given instrument and CCD the user can select the energy for which the CCD redistribution should be calculated. Through the calibration view server, `calview` inquires which "viewables" are available given the current calibration state. The list of available viewables is available in the pull down menu labeled "View". `calview` has no *a priori* knowledge of what calibration data can be viewed. Viewables can have sub-viewables. These are specialized views of a given calibration quantity. The CCF calibration files and the calibration algorithms are described in the XMM-Newton User Handbook[3].

The XMM-Newton calibration access layer (CAL) requires a calibration index file (CIF), mapping calibration types to current calibration file (CCF) constituents. The SAS task `cifbuild` builds a CIF by scanning a list of directories for CCF components. The list of directories is specified through the environment variable `SAS_CCFPATH`, or on the command line with the parameters `withccfpath` and `ccfpath`.

The list of calibration datasets comprising a CCF is ruled by two dates, i.e. (i) when the observation was performed, and (ii) when the analysis is performed. The first date is specified with `observationdate`, the second with `analysisdate`. Note that the latter can be any date (in the past or in the future) which is used to retrieve the CCF constituents applicable at the specified point in time. For instance, to generate the CIF applicable on 2008-09-10, say `analysisdate=2008-09-10`. In this way not only the time dependency of calibration is taken into account (eg. different tables of hot pixels corresponding to different dates), but also an old data calibration can be reproduced.

Normally `cifbuild` would be used to construct a CIF based on the CCF constituents available to the user. These are kept in the directories indicated either by the environment variable `SAS_CCFPATH` or in the parameter `ccfpath` specified in the call to `cifbuild`. If the CCF constituents are stored in more than one directory, the CIF must be generated so that it contains the full file path. This is specified with the parameter `fullpath`.



Calibration State Editor

Instrument	EPN
CCD	1
Node	
Filter	Open
Mode	PrimeFullWindow
CCD Temperature (K)	120
Camera Temperature (K)	120
On-Chip Binning	0
Date	1999-12-10T14:32:00
Accuracy Level	MEDIUM
Randomization	yes

Calibration Viewer State Editor

Energy (eV)	100
Theta (arcsec)	0
Phi (deg)	0
Order	0

CCF Access Log

Figure 9: Calibration State Server (`calview` task GUI).

4 Analysis of EPIC camera data

In this chapter a description is given for the analysis of XMM-Newton data sets obtained with the European Photon Imaging Camera (EPIC).

In § 4.1 the structure of the EPIC related observation data files (ODF) is discussed.

The EPIC products created by the SOC standard Pipeline processing are listed in § 4.2.

§ 4.3 explains in a rather technical way how an EPIC ODF can be re-processed up to the level of generating calibrated event lists. Such re-processing should be performed by the investigator if the calibration or the software has improved significantly between the time of the pipeline processing and the current time. While users may want to specify different time selections or different energy selections to those used in the pipeline, in general the SOC pipeline is the result of years of experience tuning the individual task parameters. Some of the analysis process described here are also synthesized in the SAS threads at:

`http://www.cosmos.esa.int/web/xmm-newton/sas-threads`

All following sections in this chapter assume that calibrated event lists exists (either from the pipeline or from a re-processing) and demonstrate how to create data products like images, spectra, rate-curves and source lists for further scientific analysis. A document describing the current status of EPIC calibration and data analysis is available from the calibration web portal (XMM-SOC-CAL-TN-0018 [12]). This document is continuously updated so it is recommended to check it with certain regularity.

4.1 The EPIC data package

After reception of the XMM-Newton observation data package from the XMM-Newton Science Archive (XSA) [4], the guest investigator wishing to analyse EPIC data is advised to verify the EPIC related content of the data package and to inspect the EPIC pipeline products (§ 4.2).

4.1.1 The EPIC Observation Data Files

The ODF names for the EPIC data will look something like:

- mmmm_iiiiiijjkk_aabeeeccfff.zzz, where
  - mmmm: revolution number
  - iiiiiijjkk: observation number
  - aa: detector ID (M1 - MOS1, M2 - MOS2, PN - pn)
  - b: flag for scheduled (S), unscheduled (U) observations, or (X) for general use files
  - eee: exposure number within the observation
  - cc: CCD identifier
  - fff: data identifier (see Table 3)
  - zzz: Format (FITS - FIT, ASCII - ASC)

Data Identifier	Contents
IME	Event list for individual CCDs, imaging mode
RIE	Event list for individual CCDs, reduced imaging mode
CTE	Event list for individual CCDs, compressed timing mode (MOS)
TIE	Event list for individual CCDs, timing mode
BUE	Event list for individual CCDs, burst mode (pn)
AUX	Auxiliary file
CCX	Counting cycle report (auxiliary file)
HBH	HBR buffer size, non-periodic housekeeping (MOS)
HCH	HBR configuration, non-periodic housekeeping
HTH	HBR threshold values, non-periodic housekeeping (MOS)
PEH	Periodic housekeeping (MOS)
PTH	Bright pixel table, non-periodic housekeeping (MOS)
DLI	Discarded lines data (pn)
PAH	Additional periodic housekeeping (pn)
PMH	Main periodic housekeeping (pn)
TMH	Thermal monitoring limits non-periodic house keeping
CIE	Compressed timing (MOS)
NOI	Noise data
ODI	Offset data (pn)
OVE	Offset / variance data (MOS)

Table 3: ODF data file identifiers relevant for EPIC analysis.

4.1.2 The EPIC MOS Observation Data Files

The most relevant files for scientific analysis of a MOS observation are (depending on the observing mode) the imaging mode and/or the timing mode event list files together with the auxiliary file providing a detailed description of each frame recorded during the exposure. The structure of these files is described in the XMM-Newton Data File Handbook [29]. One imaging mode event list file is produced per CCD by the "Full Frame" and "Partial Window" instrumental modes. In the "Partial Window" mode, the imaging area of the central chip (CCD 1) is reduced to 100×100 ("Small Window" mode) or 300×300 ("Large Window" mode) pixels. In timing mode, the central chip collects spatial info only in one dimension (the X axis) whereas the Y axis is a measure of the detection time. The six surrounding CCDs always produce imaging mode event list files using the 600×600 pixel area.

4.1.3 The EPIC-pn Observation Data Files

The most relevant files for scientific analysis of a pn observation are (depending on the observing mode) the imaging mode, the timing mode or the burst mode event list files together with the auxiliary file providing a detailed description of each frame recorded during the exposure. The structure of these files is described in the XMM-Newton Data File Handbook [29]. One imaging mode event list file is produced per CCD by the "Full Frame" and "Large Window" instrumental modes. Only CCD 4 is active in "Small Window", "Timing" or "Burst" mode. Hence these modes produce event list data only for a single chip. The other chips do not collect any data. In timing and burst mode, CCD 4 collects spatial info only in one dimension (the X axis) whereas the Y axis is a measure of the detection time.

4.2 The EPIC pipeline products

The Pipeline processing produces a number of useful products which allow a first look at the data. These are described in detail in the Pipeline Products Description document.

Within the products, the page INDEX.HTM is the main page which gives a summary of the observation and provides links to the instrument observation summary pages, of the form:

- PPooooooooooiiX000SUMMAR0000.HTM
  - oooooooooo : the Observation Identifier.
  - ii : the detector ID (EP - EPIC, OM - Optical Monitor, RG - RGS).

As well as these summary files, links to two other summary files are provided:

PooooooooooOBX000PPSSUM0000.HTM: the PPS processing summary file, and
PooooooooooCAX000XCORRE0000.HTM: the EPIC field of view cross-correlation results

With each group of the pipeline products (Table 4) there is an HTML (.HTM extension) file which lists the associated data files and gives a short description of them.

The HTML file names are of the following format:

- PPooooooooooAAAAAA000_0.HTM, where
  - oooooooooo : the Observation Identifier.
  - AAAAAA: the Group ID (Table 4).

The data file names are of the form:

- Pooooooooooiiseeeccccccbnnn.ttt, where
  - oooooooooo the Observation Identifier.
  - ii the detector ID.
  - s the scheduled flag.
  - eee the exposure number.
  - cccccc the File ID (Table 4).
  - b the instrument specific field (ISF):
    - Energy band for EPIC instruments (8: 0.2-12 keV; 1: 0.2-0.5 keV; 2: 0.5-2 keV; 3: 2-4.5 keV; 4: 4.5-7.5 keV; 5: 7.5-12 keV).
    - OM science window or OM filter code for OM products.

    * Spectral order for RGS products (1: Order 1; 2: Order 2).
- nnn the hexidecimal source number or 000.
- ttt the file type.
    * ASC: ASCII file, use Netscape, other web browser, or the *more* command.
    * FTZ: gzipped FITS format, use e.g. ds9, xmmselect, fv.
    * HTM: HTML file, use web browser.
    * PDF: Portable Data Format, use Acrobat Reader.
    * PNG: Portable Networks Graphics file, use web browser.

Table 4 lists the Group and File ID for the Pipeline processing data files relevant for EPIC.

File ID	Product Description	File Type
XCORRE	Main Cross Correlation Page	HTML
OBLSLI	EPIC Observation BOX-LOCAL Source List	FTZ
OBMSLI	EPIC Observation BOX-MAP Source List	FTZ
OMSRLI	EPIC Observation ML Source List	FTZ
OBSMLI	EPIC Summary Source List	FTZ & HTML
OSNSMP	EPIC Observation Sensitivity Map[1]	FTZ
FBKTSR	EPIC Flare Background Timeseries	FTZ & PDF
EXPMAP	EPIC Exposure Map[1]	FTZ & PNG
REGION	EPIC Source DS9 Regions	ASC
DETMSK	EPIC Detection Mask	FTZ & PNG
BKGMAP	EPIC Merged Background Map[1]	FTZ & PNG
OBKGMP	EPIC Observation Background Map[1]	FTZ & PNG
MIEVLI	EPIC MOS Imaging Mode Event List	FTZ
PIEVLI	EPIC PN Imaging Mode Event List	FTZ
TIEVLI	EPIC Timing Mode Event List	FTZ
IMAGE_	EPIC IMAGE[1]	FTZ & PNG
OEXPMP	EPIC Observation Exposure Map[1]	FTZ & PNG
OIMAGE	EPIC Observation Image[1]	FTZ & PNG
SUMMAR	EPIC Observation Summary	HTM
SFFTPL	EPIC Source FFT Plot[1]	PDF
SPCPLT	EPIC Source Spectrum Plot	PDF
STSPLT	EPIC Source Timeseries Plot[1]	PDF
SRCREG	EPIC Source DS9 Region	ASC
SRCARF	EPIC Ancillary Response Function	FTZ
BGSPEC	EPIC Source Background Spectrum	FTZ
SRSPEC	EPIC Source Spectrum	FTZ
SRCTSR	EPIC Source Timeseries[1]	FTZ
FOVRES	EPIC Field Of View Cross-Correlation Results	HTML
FOVSUM	EPIC Field Of View Cross-Correlation Summary	FTZ & HTML
SRCRES	EPIC sources Cross-Correlation results	HTML
SRCSUM	EPIC Source Cross-Correlation Summary	FTZ& HTML

1; One file per band, where the bands id are
8: 0.2-12 keV; 1: 0.2-0.5 keV; 2: 0.5-2 keV; 3: 2-4.5 keV; 4: 4.5-7.5 keV; 5: 7.5-12 keV.

Table 4: Pipeline processing data files relevant for EPIC

4.3 Running the EPIC pipeline processing

The data package received by the investigator contains EPIC pn and EPIC MOS calibrated event lists generated by the SOC pipeline processing. As the SOC pipeline is the result of years of experience tuning the individual task parameters, in general no re-processing is needed. The script of the pipeline processing (SCRCLOG) is made available to the investigator to check how the pipeline processing created EPIC products. However, investigators may consider reprocessing their data to get full advantage from the latest developments of software and/or calibration. In the case of EPIC, reprocessing can be accomplished by running the default pipeline processing meta tasks `emproc` and `epproc` (also known as `epicproc`) or the chain tasks `emchain` and `epchain` for EPIC MOS and pn respectively. The chain tasks run the calibration part of the EPIC MOS and pn pipelines in their simplest form processing all ODF components without any interaction from the user and creating calibrated EPIC event lists. As the chain tasks are scripts, they can easily be edited, allowing to produce several additional output files (mainly for diagnostic purposes).

The processing tasks are run by specifying the path to the ODF directory and applying the following task commands (it is assumed that `cifbuild` and `odfingest` have already been run; see § 2.3),

```
setenv SAS_CCF /my_work/ccf.cif
setenv SAS_ODF /my_work/<odf_name>SUM.SAS
emproc / emchain
```

or/and,

```
epproc / epchain
```

Input files are looked for in the directory entered via the `SAS_ODF` environment variable, which must also contain the general ODF files (attitude, time, summary file). Output files are created in the current directory.

For `emproc` and `epproc`, the `withinstexpids` and `selectccds` parameters allow to run `epicproc` on a subset of the data files (select a single exposure, a single instrument or a single CCD). The processing of timing modes for cases in which the pointing is offset with respect to the source, requires that the user specifies the additional parameters `withsrccoords`, `srcra`, and `srcdec`. For pn, optionally, one can use `timingsrcposition` in RAWY coordinates. In most other cases the default values are adequate.

`emproc` and `epproc` create in the current directory output data sets with the following naming convention:

Every output file name starts with a string composed by one or more of the following parts, each separated by an underscore character (_):

- rrrr: the revolution number
- iiiiiijjkk: the observation identifier (see § 4.2)
- EPN or EMOS1 or EMOS2: the instrument name

- blll: the exposure identifier. For instance: S001 (see § 4.2)
- cc: the CCD number
- nn: the node number

These parts are hierarchically structured, so that, say, any data set name that contains the exposure identifier will also contain the revolution number, the observation identifier, and the instrument name.

Additional strings indicate the contents of the data set:

- AttHk: attitude housekeeping
- Gti: GTI
- AuxGti: GTI based on the auxiliary file
- FrmGti: GTI created by `emframes` or `epframes`
- HkGti: housekeeping GTI
- Evts: the data set contains an event list
- ImagingEvts: imaging mode event list
- TimingEvts: timing mode event list
- BurstEvts: burst mode event list
- Badpixels: Badpixel files created by `badpixfind` and used by `badpix`
- Temp: a temporary data set, usually removed

Depending on the pipeline setup, some of the files above may not be produced. The default `emproc/epproc` setting produces only AttHk, Badpixels and event files. All the pipeline processing tasks inside the proc meta tasks can also be run individually by the user.

4.3.1 Running the EPIC MOS processing meta-task

A description of the functional organigram for the EPIC MOS processing is given in figures 10 and 11. The `emproc` meta task concatenates all first-level EPIC MOS tasks to produce calibrated event lists for all selected exposures.

The main subroutine (figure 10) loops over all selected exposures and instruments (MOS1/MOS2) present in the input directory. It creates one (or two, if a CCD is operated in TIMING mode) event list for a single exposure, from all relevant ODF material and (if they exist) the good time intervals generated by `tabgtigen` and the list of bad pixels (from the CCF or produced internally). In a first step (figure 11) it loops over all CCD/nodes, calling in sequence:

1. `emframes` on the auxiliary file, the event file and the external GTI file (if any), creating a frame file as expected by `emevents` and a CCD/node specific GTI file which will be re injected in the final call to `evselect`.

2. `badpix` on the event list, adding the BADPIX extension. If a bad pixels file exists, it is used instead of the CAL calls for the non-uplinked bad pixels.

3. `emevents` on the event list, the offset/variance file and the frame file, creating a new event list which will be propagated through `attcalc` and `emenergy` to `evlistcomb`.

4. `gtialign` on the external GTI file and the event file, then the task `gtimerge` to merge the resulting aligned GTI and the CCD/node specific GTI.

5. `attcalc` on the new event list, filling the X/Y columns.

6. `emenergy` on the new event list, filling the FLAG, PHA and PI columns.

Then `evselect` is called on the resulting event list(s) applying (by default) the destructive filter selection `(#XMMEA_EM) && (FLAG & 0x762a0000) == 0`. Note that in case of `emchain`, `(#XMMEA_EM)` is not applied: here events flagged as OUT_OF_FOV and REJECTED_BY_GATTI are kept in the list (as they are useful for background assessments and flare screening, respectively). For a description of the event attribute based selection, refer to the documentation of the SAS package `evatt`.

All the event list files created (one per CCD/node) are merged by `evlistcomb`, creating one event list per mode (IMAGING, TIMING). Finally `evselect` is called on the resulting events list(s), with `(CCDNR == $node$ccd) && GTI(merged GTI file,TIME)` for all CCD/nodes.

In the EPIC MOS imaging mode, the EVENTS binary table of the calibrated event list file contain 12 columns i.e TIME, RAWX, RAWY, DETX, DETY, X, Y, PHA, PI, FLAG, PATTERN and CCDNR. DETX and DETY are the event position in the focal plane array. X and Y are the event position in sky coordinates. PHA is the pulse analyser channel and PI the pulse independent channel. CCDNR is the CCD number. For a description of the FLAG column, see the documentation of the SAS package `evatt`. The PATTERN definition is given in the documentation of the task `emevents` (see also figure 16).

In the EPIC MOS timing mode, the EVENTS binary table of the calibrated event list file contains only 7 columns: the spatial coordinates RAWY, DETX, DETY, X, Y are not present as (in this mode) only one axis (RAWX) contains spatial information whereas the other axis is a measure of the arrival time of the event.

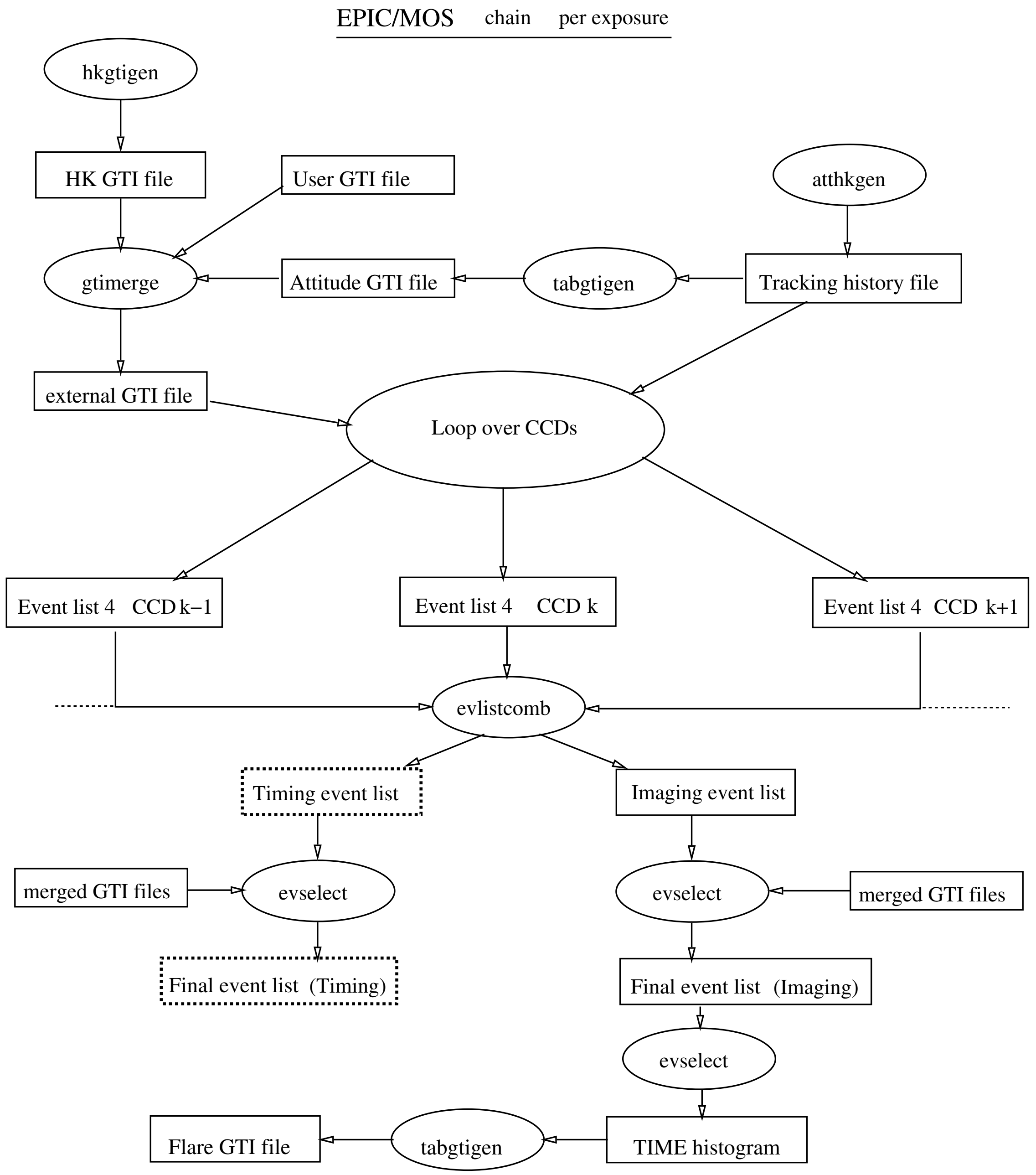


Figure 10: Organisation of the EPIC MOS chain: merging the event lists. The files in boldly dashed boxes are used (or produced) if they exist. The files in simply dashed boxes are options of the individual tasks not used in the current chain.

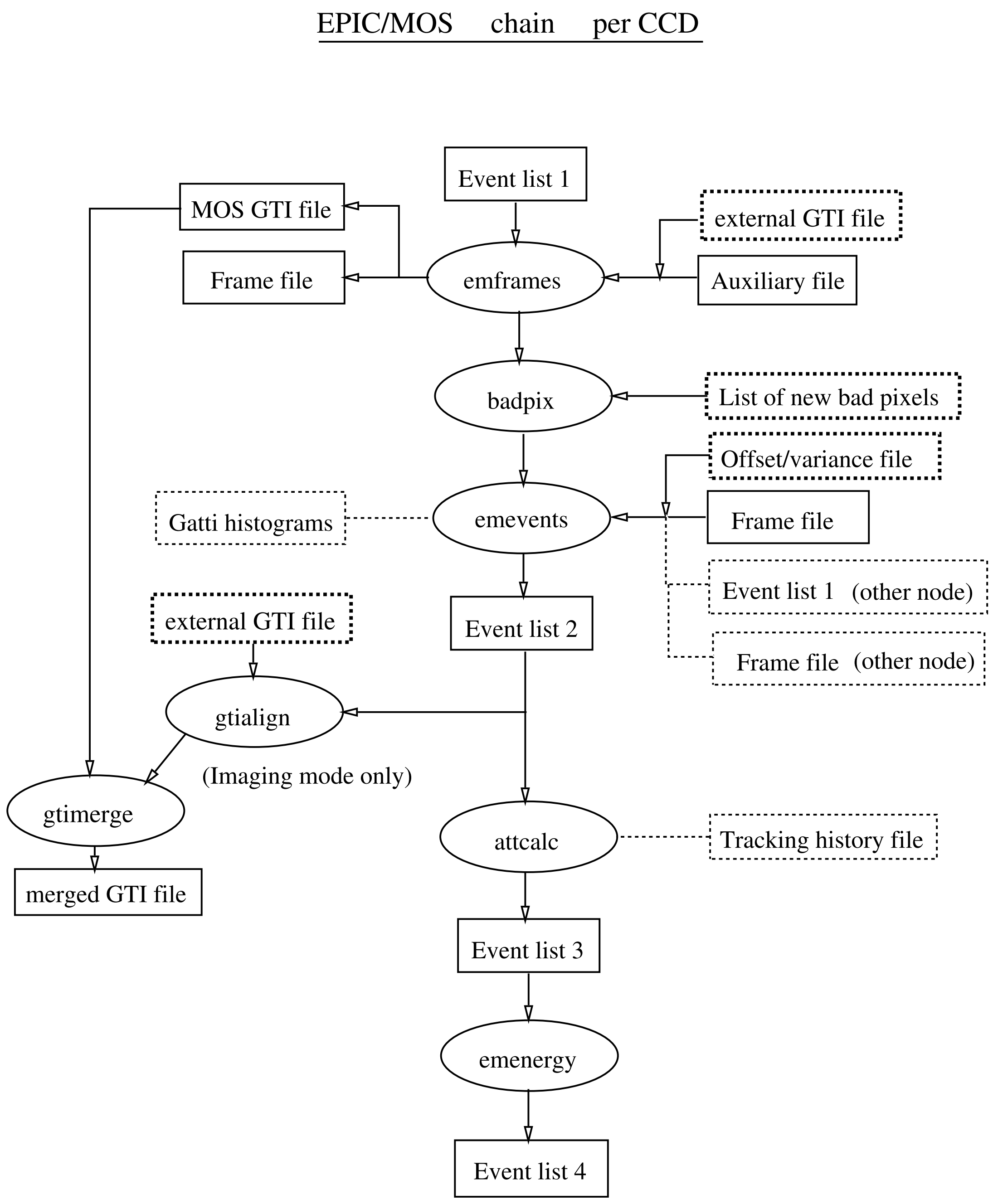


Figure 11: Organisation of the EPIC MOS chain at CCD/node level with file inputs. Same conventions as in figure 10.

4.3.2 Running the EPIC-pn processing meta-task

The EPIC pn meta task `epproc` concatenate all first-level pn tasks to produce calibrated event lists. The pn processing is sketched out in figure 12. The main subroutine (`epframes`, `badpixfind`, `badpix`, `epevents` and `attcalc`) creates one event list for a single exposure and for all selected CCDs from all the relevant ODF material and bad pixel lists calling in sequence:

1. `epframes` to process a CCD, exposure and datamode specific ODF file, creating the output raw event list and GTI data set,
2. `badpixfind` to find new bad pixels,
3. `badpix` to process the raw event list, adding the BADPIX extension,
4. `epevents` to process the event list file, flagging trailing events, performing split events pattern recognition, CTI and gain correction to create the calibrated event list and fill the PHA and PI columns,
5. `attcalc` to calculate the X and Y sky coordinates.

Finally, making use of the task `evlistcomb`, the CCD specific data sets are merged into a single event list. `evselect` selects all those events arriving in good time intervals, applies (by default) the destructive filter selection `(#XMMEA_EP) && (PI > 150 || PI < -150)` and writes the output file. For a description of the event attribute based selection, refer to the documentation of the SAS package `evatt`.

In the EPIC pn imaging mode, the EVENTS binary table of the calibrated event list file contains 14 columns i.e TIME, RAWX, RAWY, DETX, DETY, X, Y, PHA, PI, FLAG, PATTERN, PAT_ID, PAT_SEQ and CCDNR. For a description of the PAT* columns, refer to the documentation of the task `epevents`. The definition of the PATTERN values is also visualized in figure 17.

In the EPIC pn timing mode, the EVENTS binary table of the calibrated event list file contains only 9 columns: the spatial coordinates DETX, DETY, X, Y are not present as (in this mode) only one axis (RAWX) contains spatial information whereas the other axis is a measure of the arrival time of the event.

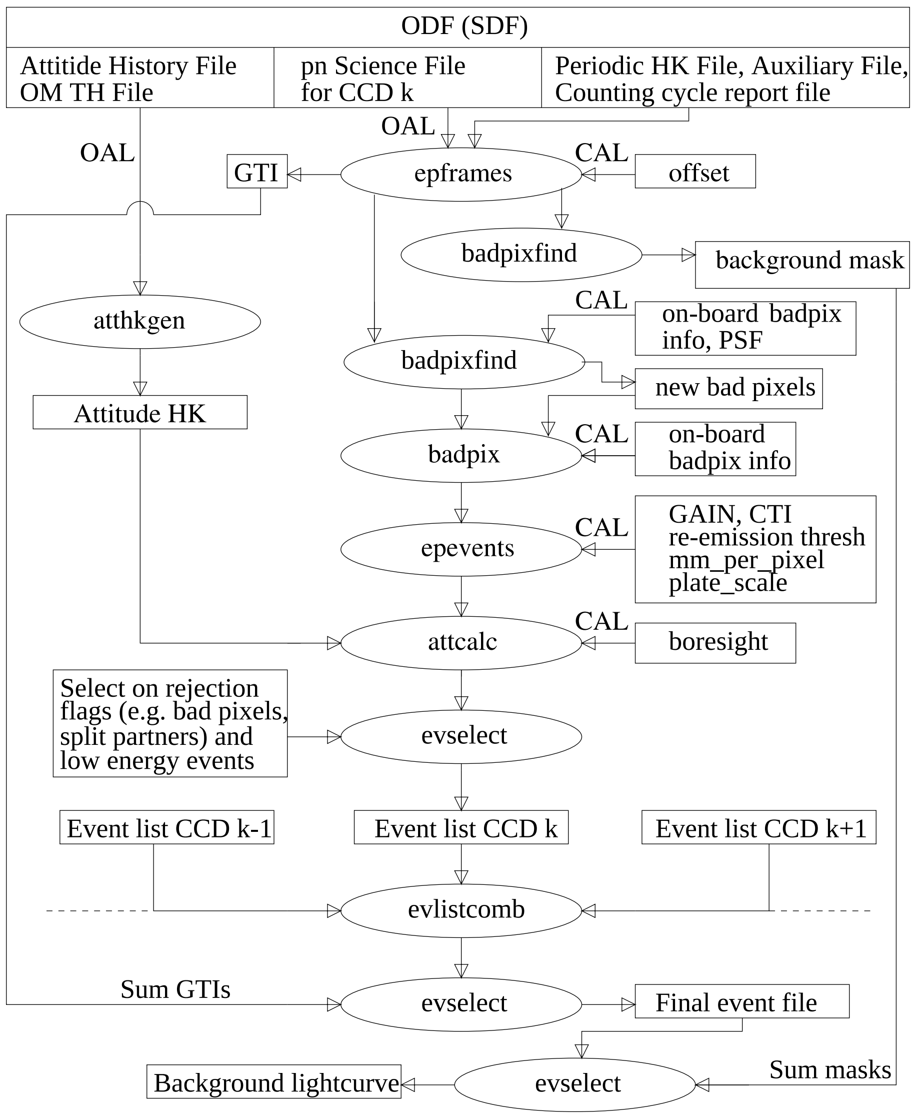


Figure 12: Pipeline processing of the EPIC-pn observation data.

4.3.2.1 Improving the quality of EPIC-pn data: `epreject`

The task `epreject` performs different actions for imaging and fast mode data. For imaging exposures, `epreject` allows the investigator to extend possible EPIC pn data analysis down to the softest energies (120 eV) for the study of soft X-ray sources. This application is described in § 4.3.2.1.1. For timing exposures, `epreject` can perform the additional tasks of flagging soft flare events and correcting for X-ray loading, both described in § 4.3.2.1.2 and § 4.3.2.1.3 respectively.

Note: As of SAS version 14.0, for imaging modes `epreject` is not run by default, but may be invoked through the `runepreject` parameter within the tasks `epproc` and `epchain`. For fast modes, `epreject` is run by default in the meta-tasks `epproc` and `epchain`. This mode dependency is controlled by a single parameter within the tasks `epproc` and `epchain`. This parameter is called `withdefaultcal` and is set to `yes` by default. For timing mode, setting `withdefaultcal=yes` implies,

```
runepreject=yes withxrlcorrection=yes runepfast=no withrdpha=yes
```

For burst mode, setting `withdefaultcal=yes` implies,

```
runepreject=yes withxrlcorrection=yes runepfast=yes withrdpha=no
```

4.3.2.1.1 Correcting EPIC-pn imaging mode data

It comprises the two following separated subtasks: [1]

1. Correcting the energy scale in specific pixels:
   The purpose of this subtask is to correct accidental shifts in the energy scale for specific pixels and thus to improve the spectral quality throughout the full EPIC-pn bandwidth. The reason for this shift are incorrect values in the offset map (caused by high-energy particles hitting these pixels during the offset map calculation), which is usually computed onboard before each observation.

   There are two methods for retrieving the affected pixels and the corresponding energy shifts: (i) directly from the transmitted offset map or (ii) from the spatial and spectral distribution of the transmitted events. The first method is more straightforward and reliable than the second one, but it requires that the offset map is available, which is not always the case.

   (i) The offset map, if available, contains for each pixel the adu (analogue digital unit, where for EPIC-pn 1 adu=5 eV) value which was subtracted from all events in the particular pixel before transmitting this information to ground. As it contains both correct and incorrect offsets, the main goal is to distinguish between both cases. This distinction is possible under the (realistic) assumption that the generic offsets

[1] **Important note:** both `epreject` subtasks require the presence of all events down to raw amplitudes PHA=20 adu (analogue digital unit, where for EPIC-pn 1 adu=5 eV).

of all pixels (not affected by electronic effects during readout) are very similar and that the areas where incorrect offsets were computed occur in isolated patches. In this case, all the information necessary for correcting accidental shifts in the energy scale can be extracted from the offset map in a straightforward way [17]. This is the default mode of `epreject`, if the offset map is available.

(ii) If the offset map is not available, then the information about the affected pixels and the corresponding energy shifts can be (approximately) reconstructed from the event file in the following way: an image is accumulated from all events which have a raw amplitude of 20 adu (the lowest amplitude transmitted). This image is then analysed for the occurrence of bright patches, and from the brightness of each patch the corresponding energy shift is reconstructed, by the method described in [17]. This energy shift is then applied to all events in the corresponding patch.

This method relies on the quality of the 20 adu image, which depends on the exposure time of the observation. In particular for short exposures, the presence of Poissonian noise in the 20 adu images limits the sensitivity for spotting the bright patches and deriving the appropriate energy correction. A parameter is supplied to the user for adjusting this sensitivity: the parameter `sigma` specifies the minimum significance which a block of four consecutive pixels along readout direction must have in order to trigger the energy correction for events in this block.

Tests indicate that `sigma`=4.0 (the default) is a good choice for short ($\sim$ 5 ks) exposures; for longer exposures this parameter can be increased (to $\sim 5-6$ for more than 20 ks). It is recommended to control the results by accumulating an image below 20 adu after this task, as this image shows then all the pixels where an offset shift was applied. In most cases, the default setting should provide a reasonable result.

A comparison of images accumulated at the lowest transmitted amplitudes, before and after applying `epreject`, should directly show the improvement in image quality which can be obtained by this subtask (figure 13).

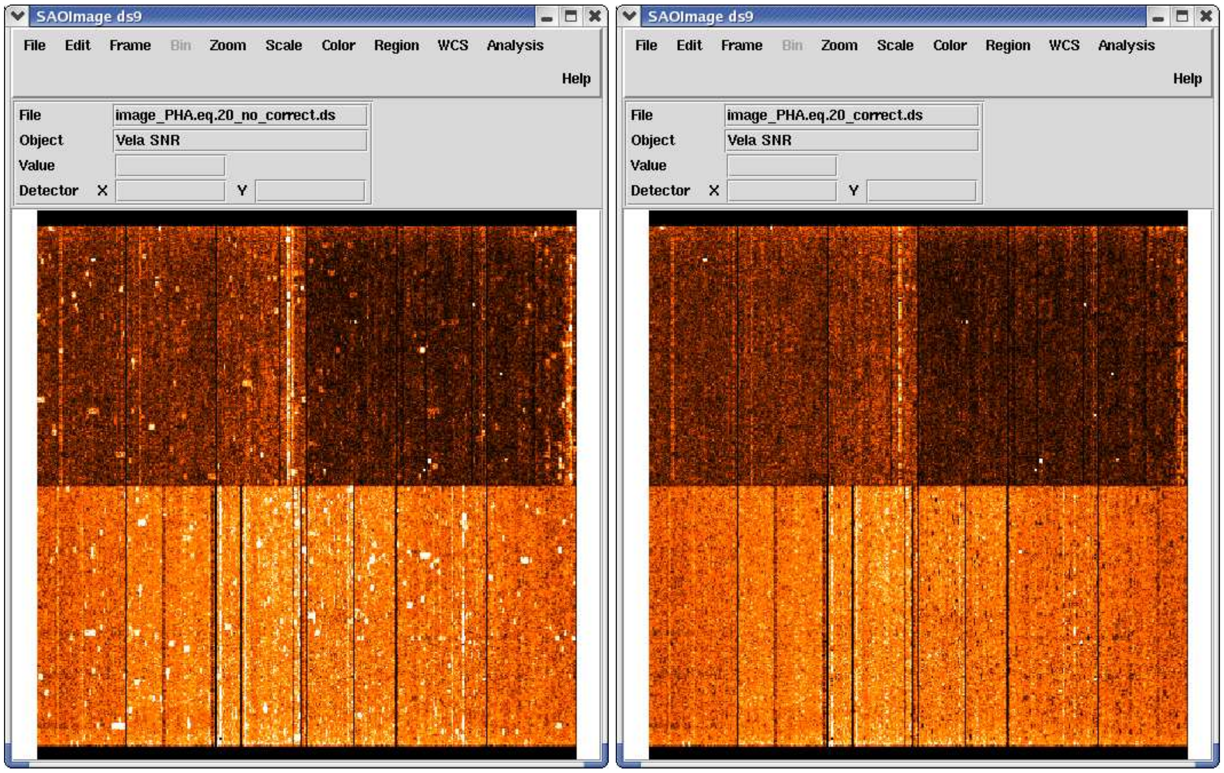
Current restriction:

After a successful run of this task, the next step in data processing would be to remove events which have received amplitudes below 20 adu by this correction, in order to ensure a homogeneous treatment of all events. Otherwise, e.g., doubles with one component below 20 adu might show up in the recombined event list, although they would be considered as singles if they had occurred at a different location at the detector. Unfortunately, SAS does not support removal of events before `epevents` is applied. Thus, the only technique currently available to reject events below 20 adu is to filter the recombined event list for PHA $\geq$ 20. This will at least remove all single events below this threshold.

Practical tips:

If one is only interested in correcting the energy scale in specific pixels, without using the noise suppression described in the next section, then the easiest application is to run `epproc` with the standard settings, adding just the `epreject` but canceling the treatment of the low-energy detector noise:

```
epproc runepreject=Y withnoisehandling=N
```


SAOImage ds9
File Edit Frame Bin Zoom Scale Color Region WCS Analysis
Help
SAOImage ds9
File Edit Frame Bin Zoom Scale Color Region WCS Analysis
Help

File image_PHA.eq.20_no_correct.ds
Object Vela SNR
Value
Detector X Y

File image_PHA.eq.20_correct.ds
Object Vela SNR
Value
Detector X Y

Figure 13: Images of all events with PHA = 20 adu in detector coordinates, before (left) and after (right) correcting the energy scale in specific pixels, but before suppressing noise events. The color scale extends from 0 to 50 events per pixel. Black patches indicate areas where no 20 adu information is available.

2. Suppressing the low-energy detector noise:
   The purpose of this subtask is to suppress the detector noise at energies below ~250 eV and should be used for qualitative imaging purposes only. The current implementation supports only Full Frame imaging mode exposures. Users should keep in mind that the nominal accuracy of the energy and effective area calibration (XMM-SOC-CAL-TN-0018 [12]) for EPIC-pn imaging modes is achieved only in the energy range 0.3-10 keV.

   While there is practically no EPIC-pn detector noise present at higher energies, X-ray data below ~200 eV are considerably contaminated by noise events. The noise properties of EPIC-pn are fairly stable in time, but vary with position and energy. This fact complicates the background subtraction at low energies, which must take both the presence of cosmic diffuse X-ray background (”sky background”) and detector noise into account.

   Compared to the sky background, the detector background is characterized by

   - a non-uniform spatial distribution: the detector background is not vignetted, but rather increases toward the CAMEX chip (to the top and to the bottom in figure 13 or figure 14) , with a steep rise in the rows closest to the CAMEX
   - a non-uniform spectral distribution: noticeable detector background is present only below a few hundred eV, with a steep rise toward the lowermost energies

This subtask is intended to simplify the background subtraction at low energies. It makes use of the fact that the noise properties of EPIC pn vary with position and energy, but are fairly stable in time. The information about the spatial and spectral dependence is used in order to flag, on a statistical basis, the amount of events which correspond to the expected detector noise [17]. Subsequent removal of such events reduces the file size considerably, extends the useful energy range down to ∼120 eV for imaging purposes only, and makes a correct treatment of the spatial and spectral properties of the detector noise more straightforward than the conventional background subtraction technique. It even includes the possibility to take temporal changes of the detector noise into account.

A further interesting consequence of this subtask is an improved treatment of out-of-time events. As described in § 4.9, such events can be suppressed by constructing an out-of-time event file from the original data set and subtracting a binned version of this data set (spectrum or image), appropriately scaled, from the original data. The out-of-time event file is produced by randomly shifting the patterns along the RAWY axis and performing the gain and CTI corrections after-wards. This method works well for energies above ∼250 eV. At lower energies, however, the detector noise is steeply rising toward the rows closest to the CAMEX. Thus, the technique of randomly shifting the patterns along the RAWY axis also spreads this noise over the column. This can be avoided if the events flagged as noise events by `epreject` are removed from the data set before producing the out-of-time event file.

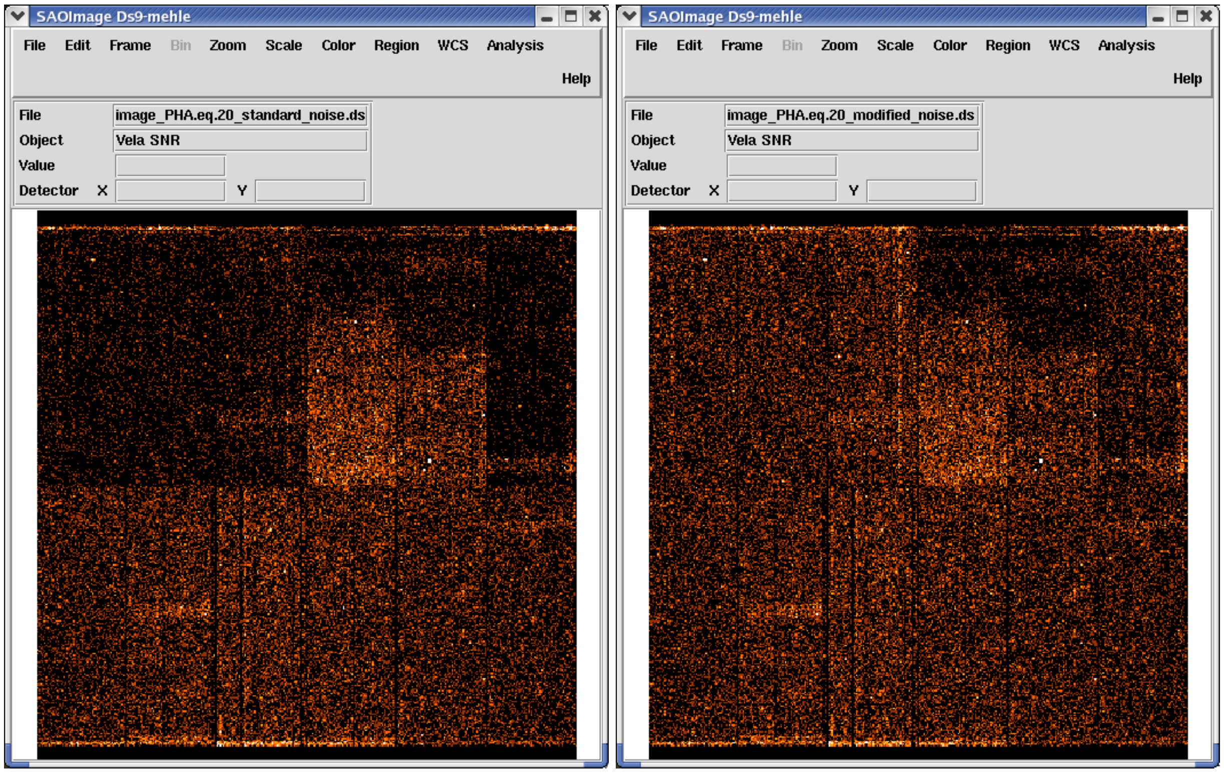
Contrary to the subtask for correcting the energy scale in specific pixels, where the default setting usually leads to reasonable results, the complexity of the noise suppression may require a fine-tuning of some settings, in order to take slight temporal changes of the detector noise into account. It is important to keep in mind that `epreject` will usually flag more than half of all the events as noise events and that the result will respond very sensitively to any change of the flagging criteria.

Parameters which can be set by the user:

There are 13 parameters which can be set by the user: a cutoff parameter and 12 chip specific correction factors, all contained in the array `noiseparameters`.

The cutoff parameter controls the maximum percentage of events in the CCFs derived from exposures with the filter wheel closed, which may be considered as noise. This parameter should be set to a value which is slightly below 100% (default: 98%), to take the fact into account that even in these exposures not all events are due to noise. There is, e.g., some additional flux present from fluorescence of the filter wheel itself, triggered by energetic particles. This component would change with the position of the filter wheel. The tests which were done so far indicate that this parameter can usually be left at its default value.

The 12 chip specific correction factors control the relative amount of noise in each CCD. These parameters may require some adjustment, in order to take slight temporal variations of the detector noise into account. These variations are often similar for all CCDs of each quadrant. The default value for all CCDs is 1.0. Increasing this number will increase the percentage of events which will be considered as noise events. Changes of these values by a few percent should be sufficient in most cases. An example of how these parameters work is shown in figure 14. The recommended way for finding the appropriate setting of these parameters is by iteration, starting with the default setting, and controlling the image which is accumulated from "no-noise" 20 adu events for homogeneity (figure 14).



File image_PHA.eq.20_standard_noise.ds
Object Vela SNR
Value
Detector X Y

File image_PHA.eq.20_modified_noise.ds
Object Vela SNR
Value
Detector X Y

Figure 14: Images of all events with PHA = 20 adu in detector coordinates, after suppressing noise events. Left: processed with the standard setting of `epreject`. Right: processed with `noiseparameters="0.98 0.97 0.97 0.97 1.0 1.01 0.96 1.0 1.0 1.0 1.0 1.0 1.0"`. The color scale extends from 0 to 5 events per pixel.

Practical tips for running `epreject` on data sets in imaging mode:

These tips are demonstrated on a specific example. The data set used for this purpose is a 33.9 ks observation (in rev. 367) of the Vela SNR, an extended soft X-ray source, which was performed in fullframe mode with the medium filter.

`epreject` operates individually on each of the 12 CCD specific event files, which can be produced by running `epframes` 12 times, e.g.,

```
epframes set=0367_0137550901_PNS00301IME.FIT eventset=rawevents01.dat gtiset=gti01.dat
...
epframes set=0367_0137550901_PNS00312IME.FIT eventset=rawevents12.dat gtiset=gti12.dat
```

This method will produce the files `rawevents01.dat` ... `rawevents12.dat`, which can then be analysed directly with `epreject`:

```
epreject eventset=rawevents01.dat withnoisehandling=Y sigma=.. noiseparameters=".."
 ..
epreject eventset=rawevents12.dat withnoisehandling=Y sigma=.. noiseparameters=".."
```

This process will add the columns `OFF_COR` and `NOISE` to the files `rawevents01.dat ..  rawevents12.dat`, where the `NOISE = 1` flag marks events which were considered as having been caused by detector noise (otherwise `NOISE = 0`). The column `OFF_COR` contains the adu values which were subtracted from the PHA values in order to readjust the energy scale in specific pixels. This column is present for the purpose of information and in order to avoid multiple corrections if `epreject` is run several times. As `epreject` has no destructive effect on the event file, it can be run repeatedly on the same file; the original information will be automatically restored at the beginning of this task.

Please note that, when `epreject` is called directly, all 12 CCD specific noise correction factors have to be given in each of the 12 `epreject` commands, although only one of them will be used in each command.

From the 12 `rawevents*.dat` files, images can be binned which contain only the "no-noise" events at the lowest transmitted energies (where such checks are most sensitive), e.g.:

```
evselect table=rawevents01.dat withimageset=true imageset=i01.fits \
         xcolumn=RAWX ycolumn=RAWY \
         imagebinning=binSize ximagebinsize=1 yimagebinsize=1 \
         expression="PHA.eq.20 .and. NOISE.eq.0"
```

Such images (for all 12 CCDs) should contain a similar density of events in the regions which are free from bright X-ray sources.

In this example (figure 14, right), a reasonable parameter setting was found to be `noiseparameters="0.98 0.97 0.97 0.97 1.0 1.01 0.96 1.0 1.0 1.0 1.0 1.0 1.0"`. This assigns noise flags to the following percentage values of all events:
`42.5% 48.8% 59.9% 21.9% 29.1% 42.7% 57.4% 57.1% 61.9% 69.7% 74.6% 79.4%`

For comparison, the default setting `noiseparameters="0.98 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0"` flags the following percentages of events as noise, for CCDs 1-6: `43.8% 50.3% 61.8% 21.9% 28.8% 44.5%` (figure 14, left).

These percentages vary from observation to observation. If there are no bright X-ray sources in the field of view, they can be considerably higher.

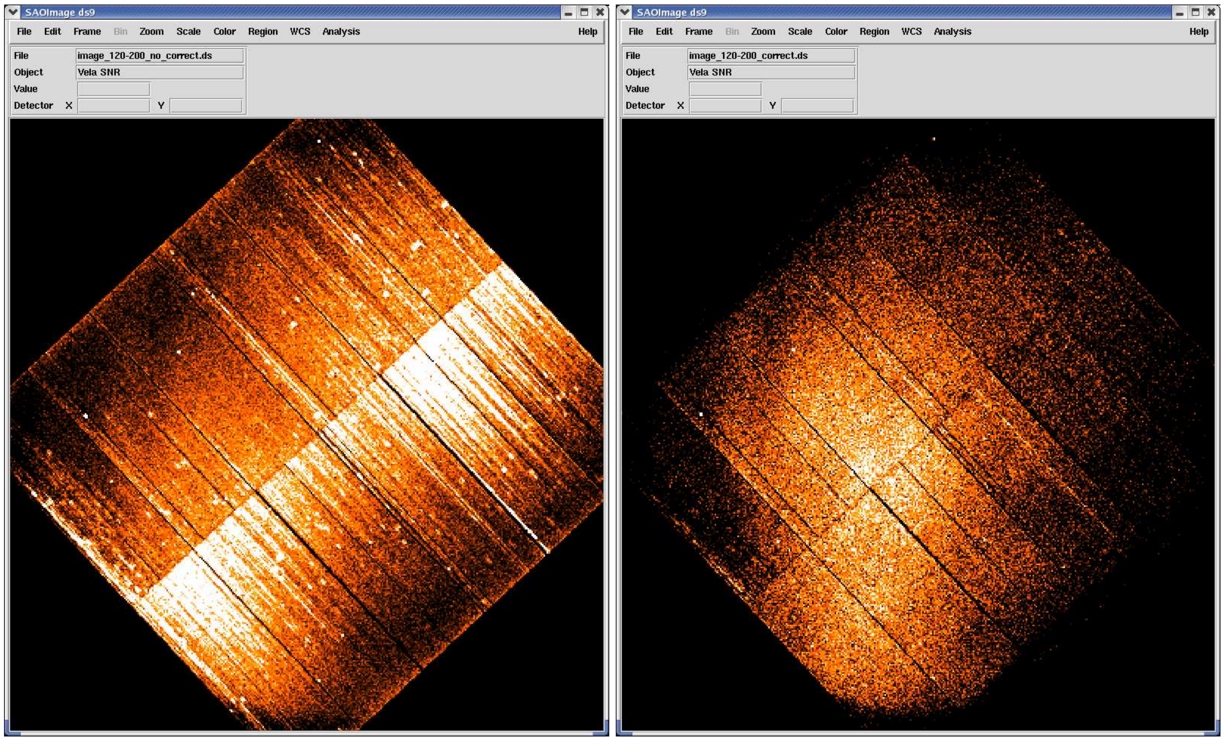
Once an appropriate setting has been found, the full `epchain` can be run with these settings, e.g.:

```
epproc runepreject=Y withnoisehandling=Y sigma=4.0 \
      noiseparameters="0.98 0.97 0.97 0.97 1.0 1.01 0.96 1.0 1.0 1.0 1.0 1.0 1.0" \
      filterevents=Y filterexpression="#XMMEA_EP .and. PI.gt.0. .and. PHA.ge.20"
```

The `filterexpression` ensures that no events are removed regardless of their energy (unless they are regarded as noise events). This will allow to extend the useful energy range down to ∼120 eV. Events with `PHA` <20 adu, which are the result of correcting the energy scale in specific pixels, should be removed in order to get a homogeneous data set.

In figure 15 Vela SNR images in the very soft (120 - 200 eV) energy band processed without and with `epreject` are shown. This demonstrate the type of data quality improvement that one can expect to achieve for imaging mode EPIC pn data. Both images were produced with the following command (see § 4.7 for details on the generation of EPIC images):

```
evselect table=P0137550901PNS003PIEVLI0000.FIT withimageset=true \
         imageset=image.fits xcolumn=X ycolumn=Y \
         imagebinning=binSize ximagebinsize=100 yimagebinsize=100 \
         expression="PHA.ge.20 .and. PI.gt.120 .and. PI.lt.200"
```


SAOImage ds9
File Edit Frame Bin Zoom Scale Color Region WCS Analysis Help
Value
Detector X Y

File image_120-200_no_correct.ds
Object Vela SNR

File image_120-200_correct.ds
Object Vela SNR

Figure 15: Vela SNR images in the energy range 120-200 eV, in sky coordinates. Left: processed without `epreject`, scale: 0-40 events/pixel. Right: processed with `epreject`, scale: 0-20 events/pixel.

4.3.2.1.2 Flagging soft flare events in EPIC-pn timing mode data

The `epreject` task also offers a method to flag so-called "soft flare events" in EPIC pn timing mode data: The timing mode was designed for observing bright variable sources with a very high time resolution. Up to now it has been possible to use the spectra down to 500 eV in this mode. Below this energy the data are affected by so-called soft flares which are caused by stack overflows generated by high energy particles. These soft flares have a sharp rise (from 0 counts/s to several thousand counts/s in ∼0.10-0.15 s) then decaying back to 0 counts/s slightly slower in about 0.3-0.4 s). In some cases (extremely bright flares) they can lead to a FIFO overflow thus causing a small gap in the data of about ∼0.08 s. These gaps are handled by the SAS.

`epreject` provides a method to mitigate the effect that these flares have on the data by flagging such soft flare events so that they can later be screened from the data.

With this method it becomes possible to use the spectral information in the data down to the lowest energies detectable in the pn timing mode i.e. 200 eV.

This is particularly interesting for timing studies of isolated neutron stars, X-ray binaries and other variable objects, such as magnetic CVs, with very soft spectra.

In order to perform the soft flare event selection, the `withsoftflarescreening` parameter in `epreject` must be enabled. The programme then generates a light curve in 0.1 s bins in the specified PHA range (parameter `softflareenergyrange`, default: 40-50 ADU) using the output event lists from the `epframes` task. The light curve is smoothed with a boxcar function whose width can be modified via the parameter `softflaresmoothparams`. This smoothed light curve is then used to perform the soft flare event selection: each event is checked to see whether it has a PHA value in the user given PHA range and the light curve is above the user given threshold (parameter `softflarethreshold1`; this value has to be optimised for each observation as the contribution of the source photons in the given PHA range varies a lot from observation to observation).

Again, `epreject` has no destructive effect on the event file: A flag column labeled `Flare` is added to the rawevents file. A "1" in this column denotes that an event has been flagged as a soft flare event. This column can be used to screen the data.

The user should check the `epreject` task description for information on caveats to keep in mind when interpreting the pn timing mode data down to 200 eV.

4.3.2.1.3 Correction for X-ray loading in EPIC-pn fast mode exposures

X-Ray Loading (XRL) occurs whenever source counts contaminates the offset map taken prior to each EPIC-pn exposures. Instrument operations have been configured in such a way that XRL should never occur, if the appropriate combination of instrument mode and filter is selected based on the brightness of the primary target. However, it has been discovered that almost all the exposures taken in EPIC-pn fast Modes (Burst and Timing Mode) until the 23rd of May 2012 were unexpectedly affected by XRL. As of that date offset maps in these modes are being taken with the optical blocking filter in the CLOSED position, thus preventing source contamination.

As of SAS version 14.0, the reduction meta-tasks `epproc` and `epchain` run the XRL correction by default. Users are discouraged from interactively using `epreject` for this purpose.

4.4 Filtering calibrated EPIC event lists

EPIC calibrated event lists must be processed to generate data products including images, spectra and rate curves.

All product creations can be accomplished using the `evselect` task or (via a user friendly Graphical User Interface; GUI) the `xmmselect` task. The event list is filtered on the fly according to user-specified selection criteria. The filtered event list can be stored on disk and/or products can be extracted from this filtered event list.

The filtering process is carried out on an event-by-event basis controlled by user-specified selection criteria. These criteria take the form of character strings which can be composed of a variety of elements including numerical and logical constants, operators, functions, and attributes. Arithmetic and logical operations, file-based filtering, new column or arrays construction and symbolic reference to other arrays can be performed.

Events for which the selection expression does not evaluate to true will be marked as invalid or discarded from the data set and shall not be considered in the product extraction. `xmmselect` (and `evselect`) support selections based on intrinsic event attributes falling into the following sub-categories.

1. Spatial selections in raw pixel (RAWX/RAWY), camera coordinates (DETX/DETY) or sky pixel (X/Y) space, or in any spatial coordinate system. Special pre-defined region shapes exists such as CIRCLE, ELLIPSE, ANNULUS, BOX, POLYGON. Spatial filtering with mask images or region files is possible as well.

2. Energy selections in the form of one or more interval specifications in either PHA or PI space.

3. Time selections in the form of interval specifications or Good Time Interval (GTI) files created with e.g. `tabgtigen`.

4. Event selections based on informational and rejection attributes (see `evatt` package description for details).

5. Event selections based on any other event properties (e.g. PATTERN or CCDNR).

The user should consult the `selectlib` package description which details the syntax and semantics of the expressions driving the above operations and gives sample expressions to demonstrate typical usage scenarios.

Note, while all of the data products generation can be done on the original event list, it can save significant computing time and memory first to create a filtered event list (e.g. removing high flaring background periods, restricting the analysis to certain regions and energies) and operate after-wards on the reduced filtered event file.

4.4.1 Filtering EPIC MOS concatenated event lists

Each of the two EPIC MOS cameras consists of seven individual 600 x 600 pixel CCDs. Because of telemetry constraints, a real time on-board recognition scheme filters out cosmic-ray tracks and exclusively transmits to the ground the information supposedly related to X-ray events. The on-board recognition scheme looks for a local enhancement of signal in flat fielded images. The signal enhancement is searched in 5 x 5 pixel matrix which is scanned over the full image. The signal is defined with respect to a threshold value set by telecommand for each observation. An event is identified if, in the 5 x 5 pixel matrix, pixels above thresholds formed a predefined pattern.

In the case of imaging mode, 32 patterns have been predefined (see figure 16, upper panel). Each one of them correspond to an isolated event i.e. to a zone above threshold completely encircled by pixels below threshold. There are however two exceptions. Pattern 30 can be connected to a pixel above threshold on the diagonal of the center pixel. Pattern 31 can have any of the border pixels above threshold. Pattern 30 and pattern 31 are designed to quantify the amount of cosmic-rays extended tracks.

On-ground calibration of the imaging mode has shown that soft X-rays mainly generate patterns 0 to 12 corresponding to compact regions of X-ray energy deposition. Pattern 0 events are single pixel events. These comprise most of the valid X-ray events with the most accurate energy resolution. For imaging mode data patterns 0 to 12 are the canonical set of valid X-ray events which are well calibrated. Selection of these patterns constitutes the best trade-off between detection efficiency and spectral resolution. However, because they deposit energy below the CCD depletion zone, higher energy X-rays also generate pattern 31 events with a probability of 20% and 50% respectively at 6 keV and 9 keV. Pattern 31 comprises largely cosmic ray events but can also include pile-up X-ray events. A large density of pattern 30, 31 events (and 26−29 diagonal events) in the core of the telescope point spread function (PSF) is the signature of a piled response which needs careful analysis (see § 4.5).

In the case of timing mode data, the pattern analysis is purely 1-dimensional (i.e. insensitive to other rows, see figure 16, lower panel), because each timing ”row” is actually the sum of 100 true rows, so the rows are not physically related.

High electronic noise affects occasionally some of the MOS cameras CCDs ([14]). This effect appears most frequently, but not exlcusively, in MOS2 CCD5 and is limited to the soft ($\leq$1 keV) energy range. It has been present in short phases since the beginning of the mission, but became continous on this CCD since Rev.#874. The causes are still unknown, and a correction is not available. SAS users can flag CCD affected by enhanced electronic soft X-ray noise using the task `emtaglenoise`, which populates keywords LENOISnn in the header of a calibrated event list (a value of '1' means that the CCD is noisy). Optional parameters `filterbadccds` and `filteredset` should be used if the user wants to remove *all events* in *all CCDs* tagged as noisy by `emtaglenoise`. If `MOS1.evt` is the event lists produced by `emproc`, `emchain`, or the pipeline processing, use the following command to flag noise CCDs:

```
emtaglenoise eventset=MOS1.evt filterbadccd=yes filteredset=MOS1_filtered.evt
```

General recommendations on filtering schemes for the generation of images and spectra are given

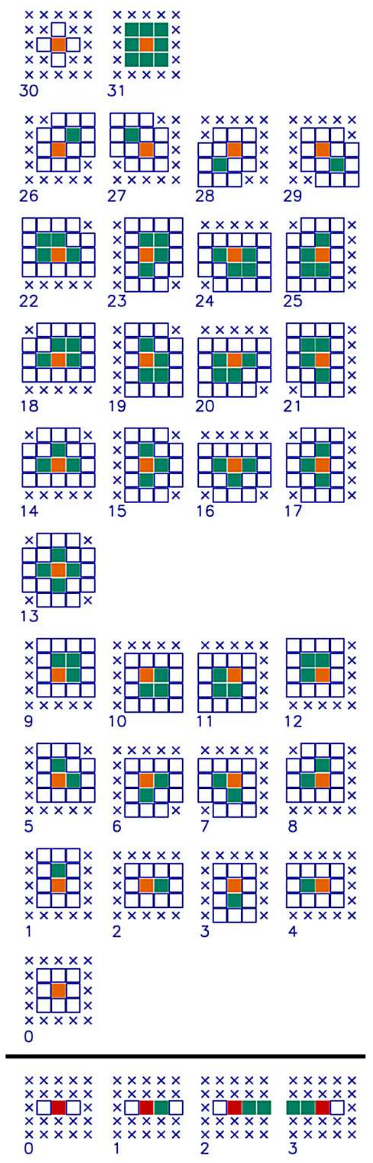


Figure 16: List of valid EPIC MOS patterns: the *upper panel* for **imaging mode** should be interpreted as follows: each pattern is included in a 5 x 5 matrix used for proximity analysis, a pattern is centered by definition on the pixel with highest charge, this central pixel is colored in red, the other pixels above threshold in the pattern are colored in green, all pixels colored in white must be below threshold, the crossed pixels are indifferent (they can be above threshold). The philosophy for patterns 0-25 is that a good X-ray pattern must be compact, with the highest charge at the center, and isolated (all pixels around are below threshold). Patterns 26-29 are the so-called diagonal patterns, not expected from a genuine X-ray, but which can arise in case of Si-fluorescence or of pileup of two monopixel events. The *lower panel* for **timing mode** should be interpreted in the same way as in imaging mode, with the difference that the place where maximum charge occurs is ignored. Due to this, all doubles appear as Pattern 1, whether leading or trailing. Patterns 2 and 3 are mostly not due to true X-rays, but to cosmic-ray tracks.

in XMM-SOC-CAL-TN-0018 [12], a document describing the current status of EPIC calibration and data analysis.

4.4.2 Filtering EPIC-pn concatenated event lists

The EPIC pn camera consists of twelve 64 x 200 pixel CCDs on a single wafer. For full frame and extended full frame modes the first 12 rows at the readout node are not transmitted to ground (are set to "bad", equivalent to "bad pixels"). In contrast to the MOS, all non bad pn events supposedly related to X-rays are transmitted to the ground and the pattern recognition and recombination of split partner is done off-line by the task `epevents`. Filtering of an EPIC pn dataset is entirely performed by the EPIC pn pipeline processing. The user is only advised to check the background level as a function of time, with as main aim the identification of any periods of enhanced low-energy proton flux, see § 4.4.4.

For pn, 13 valid patterns have been defined. As in case of the MOS, pattern 0 events are single pixel events. These comprise most of the valid X-ray events with the most accurate energy resolution. For image analysis patterns 0 to 12 (see figure 17) are the canonical set of valid X-ray events. All higher patterns are not created by single X-ray photons and are due to pattern pileup. For spectral analysis however, only single and double (pattern 0 to 4) should be used, because only these are well calibrated. For the timing mode only singles plus doubles (pattern 0 to 4) should be selected for spectral analysis. Selection of these patterns constitutes the best trade-off between detection efficiency and spectral resolution.

Users need to beware of the spatial non-uniformity of low energy multi-pixel events, e.g. when defining source and background accumulation regions (§ 4.8.1).

4.4.3 How to get pixels flagged "ON_BADPIX" back into the eventlist

Using the recommended selection expressions `#XMMEA_EP` and `#XMMEA_EM`, or even the more restrictive `FLAG==0`, pixels flagged as bad are not taken into account in the analysis. For specific circumstances it might be desired to revise a bad pixel flag and to make the pixel available again to the analysis using the task `ebadpixupdate`.

An important point regarding the bad pixels is that there are essentially three separate (though not exclusive) sets of bad pixels that must be dealt with. These are (1) bad pixels up-linked to the satellite and eliminated on-board, (2) bad pixels identified in the CCF but not up-linked, and (3) additional bad pixels associated with the particular observation in question. A corresponding list of bad pixels, individually for each CCD, is provided by the BADPIX**-extension tables inside the eventlist FITS-file.

- **Create eventlist files still containing bad pixels.** Per default, all EPIC pipeline processing tasks (`e[m/p]proc` or `e[m/p]chain`) perform the search for bad pixels both in CCFs and in the individual observation and flag the corresponding events from these bad pixels in the temporary eventlists. However the treatment of bad pixels at the time of the creation of the final eventlist file is different for the pn and the MOS pipeline tasks. The pn tasks take over the events from bad pixels into the final event list and assign to them the `FLAG==ON_BADPIX`, whereas the MOS tasks filter out these bad pixel events such that they do not appear any more in the final eventlist file. To get the MOS bad pixels back into the eventlist, it is necessary

```
                      . . .
single event          . X .
                      . . .


                    . . . . .   . . . . .   . . . . .   . . . . .
                    . . x . .   . . . . .   . . . . .   . . . . .
double pattern      . . X . .   . . X x .   . . X . .   . x X . .
                    . . . . .   . . . . .   . . x . .   . . . . .
                    . . . . .   . . . . .   . . . . .   . . . . .


                    . . . . .   . . . . .   . . . . .   . . . . .
                    . . x . .   . . x . .   . . . . .   . . . . .
triple pattern      . x X . .   . . X x .   . . X x .   . x X . .
                    . . . . .   . . . . .   . . x . .   . . x . .
                    . . . . .   . . . . .   . . . . .   . . . . .


                    . . . . .   . . . . .   . . . . .   . . . . .
                    . m x . .   . . x m .   . . . . .   . . . . .
quadruple pattern   . x X . .   . . X x .   . . X x .   . x X . .
                    . . . . .   . . . . .   . . x m .   . m x . .
                    . . . . .   . . . . .   . . . . .   . . . . .
```

Figure 17: List of valid EPIC-pn patterns (cf. figure 16). Here "." marks a pixel without an event above threshold, "X" is the pixel with the maximum charge ("main pixel"), "x" is the pixel with a non-maximum charge, "m" is the pixel with the minimum charge. These 13 figures refer to the SAS PATTERN codes 0 (singles), 1-4 (doubles), 5-8 (triples) and 9-12 (quadruples), respectively. The RAWX co-ordinate is running rightward and the RAWY co-ordinate running upward.

to re-run the MOS pipeline tasks using a special parameter to switch off the final filtering:

```
emproc flagfilteredevents=yes
```

or

```
emchain rejectionflag=764ba000
```

The use of the `emchain` parameter `rejectionflag=764ba000` is recommended (instead of `rejectbadevents=no`) because `emchain` keeps the events flagged as being ON_BADPIX while it still removes all other types of bad events.

- **Extract bad pixel table from the eventlist file.** The eventlist FITS files contain individual bad pixel tables of all CCDs. These tables can be extracted with the Ftool `fv`. After opening the eventfile with `fv <eventlist_name>`, two windows appear: a general `fv` menu window and a window listing FITS headers and tables of all extensions inside the eventlist file. The extensions of the bad pixel tables are named BADPIX** with ** being the CCD number. The bad pixel table of a specific CCD is presented in a separate window if the `All` button under the `Table` column is pressed. The table contains for each entry the pixel position in RAWX/RAWY coordinates, an extension size within the column (YEXTENT), the TYPE (1=hot, 2=flickering, 3=dead) and the BADFLAG indicating to which of the sets the bad pixel belongs: (1) for onboard bad pixel table, (2) for CCF bad pixel table and (3) for detections via the `ebadpixupdate` task.

To extract one or more bad pixels tables, mark the corresponding extensions in the `Index` column and chose `Export HDUs...` from the `File` menu. Of course `fextract` (and `fappend`, if several bad pixel tables are required) does the job as well.

- **Edit the bad pixel table.** After saving the extracted bad pixel tables in a new file, open this new file using `fv` and open the table you want to edit. To delete a bad pixel entry, mark the corresponding row by clicking on the row number and chose `Edit` → `Delete` → `Selected rows` from the `Edit` menu. Because bad pixels with BADFLAG=1 are eliminated onboard, these pixels cannot be recovered and their entries must not be changed. You have to pay attention on the YEXTENT column for the corresponding pixel entry. A single bad pixel has YEXTENT=1. If just one bad pixel within an extended region within a column should be recovered, the YEXTENT value can be edited directly. It might be necessary to add an additional row (`Edit` → `Insert` → `Row`) to define the remaining bad pixels in the column correctly. Save the changed bad pixel table (`File` → `Save`).

- **Update the bad pixel tables in the eventlist file.** The last step is to update the FLAG column inside the eventlist. This can be done by the task `ebadpixupdate`. The task needs as input the changed bad pixel tables and the eventlist file. The following example shows the update of an EPIC eventlist EPICEVENTLIST.FIT. The original bad pixel tables of all 12 CCDs have been exported to a file BADPIXTABLE.FIT. The bad pixel tables of CCD1 and CCD3 have been changed. The FLAG keywords inside the eventlist file are updated by the command:

```
ebadpixupdate eventset=EPICEVENTLIST.FIT fromccf=N overwrite=yes \
              badpixtables='BADPIXTABLE.FIT:BADPIX01 \
              BADPIXTABLE.FIT:BADPIX03'
```

4.4.4 Filtering high background periods

The user is advised to produce a histogram of TIME values (a rate curve) in order to identify the useful period of low background level when the focal plane is not illuminated by low-energy protons.

Before any filtering, the user is also advised to inspect the background light curves produced by the SOC pipeline processing (FBKTSR), where all sources and bright features/pixels have been masked out (see task descriptions of `emchain` and `epchain` for further details). If bright hard point-like sources are in the FoV, such sources should be excluded prior to the interactive rate curve generation as well.

In order to check for and remove any additional high background periods from the event list, the user can apply the following recipe:

- Build a rate curve of the TIME column in the calibrated event list using only valid single events with energy greater than 10 keV. This can be performed using `xmmselect` by entering 10000 in the PI lower limit box (in case of the pn in addition the PI upper limit should be set to 12000 avoiding noisy pixels with energies above 12 keV), 0 in the PATTERN upper limit box, pressing the PI and PATTERN button, and in addition appending `&& #XMMEA_EM` in case of MOS, or `&& #XMMEA_EP` in case of pn in the filter expression box. The round radio button in the TIME row should then be pressed. A suitable time bin needs to be selected for the OGIP rate curve accumulation, e.g. 25, 50 or 100 seconds, depending on the exposure duration.

- Examine the rate curve produced and identify periods with a constant low count rate and periods with a high background level. Select a suitable count rate threshold which lies a little above the low background rate. Recommended values are 0.35 counts/s for the MOS and 0.4 count/s for the pn camera, respectively, but depend on the science the user wants to do, and on the source signal-to-noise.

- Assuming that the rate curve is named `rates.fits`, a new GTI file can be created from the selected count rate threshold using a command line as follows (the example holds for the MOS; change the count rate value for pn accordingly):

  ```
  tabgtigen table=rates.fits gtiset=BKG_GTI.fits \
            expression='RATE < 0.35'
  ```

- This GTI selection can then be passed to the existing event list using:

  ```
  evselect expression='gti(BKG_GTI.fits,TIME)' ...
  ```

  When using `xmmselect` from the GUI, the above expression should be typed in the "Selection expression" window.

Low background intervals might differ significantly between different EPIC cameras and therefore a GTI created for one EPIC camera should not blindly be used for all the other cameras as well.

Users can also make use of GTIs which were created to make the pipeline images (only these - not the pipeline created event lists - have the flaring background removed): [2]

```
evselect table=inevlist.fits \
         filtertype=dataSubspace dssblock=image.fits:PRIMARY \
         keepfilteroutput=yes withfilteredset=yes filteredset=outevlist.fits
```

where `inevlist.fits` is the input event list (e.g. from the pipeline), `image.fits` is the pipeline image from which to take the GTI and `outevlist.fits` is the output flare GTI filtered event list. If the user prefers the task `xmmselect` to apply such pipeline processed GTI to an input event list, the "Filtered table" product selection needs to be started. On the "General" `evselect` GUI parameter page, the "Filtering" method must be changed to "dataSubspace" and other `evselect` parameters need to be set as in the example above.

[2]Note, that due to a backward incompatibility since the introduction of `param-2.0`, this method only works if the pipeline image also has been generated with SAS v6.0 or later.

A third method to clean an EPIC event list from flaring background is offered by the SAS task `espfilt`. `espfilt` applies a user-selected method for filtering an event list of cosmic soft proton events. The filtering produces a new event list, lightcurves of the object and corners of the detector (where X-rays produced by cosmic soft proton events are registered), raw and filtered images and a plot of the lightcurves and GTIs. In contrast to the cleaning methods described above, which are based on a rate lightcurve threshold, `espfilt` creates a histogram of rate values from the light curve and finds the most likely value, assuming that to be similar to the mean of the quiescent rate. The task then fits a Gaussian to a small window around that value in the histogram to determine the true mean and dispersion of the quiescent background rate. `espfilt` then excludes time intervals with rate higher than a multiple of the dispersion above the mean quiescent background and excludes good regions shorter than some limit.

4.4.5 Correcting an EPIC-pn event file for spatially-dependent CTI effects.

As of SAS v12.0, the task `epspatialcti` allows to correct an EPIC-pn event file for spatially-dependent CTI effects. Measurements of the spectra of bright extended sources have shown that there is a pixel-to-pixel variation in the energy scale which is mainly caused by CTI changes due to partial trap saturation. `epspatialcti` corrects for this effect making the response much more uniform.

This task should be run on the event file produced after all of the other CTI and gain corrections have been applied. That is to say, on the event files produced by `epproc` or `epchain`. It is currently recommended to apply this correction for observations taken in FullFrame and ExtendedFullFrame modes. There is some evidence that it may also produce an improvement in LargeWindow and SmallWindow modes, however, it should not be applied for Timing mode or Burst mode observations.

The task implements two methods for spatial CTI corrections, both accesible via the task parameter `SD20mode`. By default, the Sanders et al. ([13]) method will be applied.

To avoid the corrections being applied twice, a keyword `SPATCTIC` is set in the header of the `EVENTS` extension when the task terminates successfully.

4.4.6 Correcting an EPIC-pn event file for energy shifts.

As of SAS v21.0, the task `evenergyshift` allows to add an ad-hoc energy shift to EPIC-pn events in an event file, taken from observations made with the FastTiming or FastBurst modes.

The task calculates the initial energy of the photon arriving in a CCD, using a large number of corrections based on temporal, spatial and energy information. Nevertheless, in some cases, the photon energies can still be seen to be shifted from their true positions, when modelling the spectrum in a spectral fitting package. This becomes obvious by looking at residuals which are visible around the Si K_α line at 1.84 keV and the Au-M edge at 2.2 keV and AU-L edge at 11.9 keV.

A SAS thread illustrates how to apply the corrections using `evenergyshift`, Correct for rate-dependent energy scale effects in the PN Burst and Timing mode.

4.5 Pile-up

Pile-up occurs when a source is so bright that the possibility that two or more X-ray photons deposit charge packets in a single pixel (”photon pile-up”), or in neighboring pixels (”pattern pile-up”, i.e. singles pileup to doubles etc.), during one read-out cycle (i.e. one frame) is non-negligible. In such a case these events are recognized as one single event having the sum of their energies. If this happens sufficiently often, this will result in a hardening of the spectrum as piled-up soft events are shifted in the spectrum to higher energies, unless the sum of the energies is higher than the threshold for event rejection onboard.

In addition, pile-up leads to a more or less pronounced depression of counts in the central part of a bright source, resulting in flux loss. Pile-up also affects light curves, suppressing high count rates.

The XMM-Newton User Handbook [3] lists (readout mode dependent) maximum count rates above which a source suffers from pile-up. In general the MOS camera is much more susceptible to pile-up than the pn for the same intrinsic source flux. Single (i.e. `PATTERN`=0) event spectra are typically less sensitive to pile-up.

To check whether pile up indeed is a problem, use the SAS task `epatplot`. There is a SAS dedicated thread at:

http://www.cosmos.esa.int/web/xmm-newton/sas-threads

To run `epatplot` one needs to create an event file for the source as described below in step 3) of § 4.8.1. The input event file name (e.g., `src_evlist.fits`) must be specified via the `epatplot` task `set` parameter. If the resulting plot shows the model distributions for single and double events diverging significantly from the measured distributions, this is a strong indication that pile-up has occurred. Figure 18 shows an example of a bright source observed in pn full-frame mode which is strongly affected by pile-up. Due to ”pattern pile-up” more doubles are produced at the expense of single pixel events.

A common strategy adopted to analyse spectra of piled up sources has been to excise the core of the point-spread function (PSF). The method of excising the inner part of the source emission region from the event list used for the creation of the spectrum, can be done with the help of

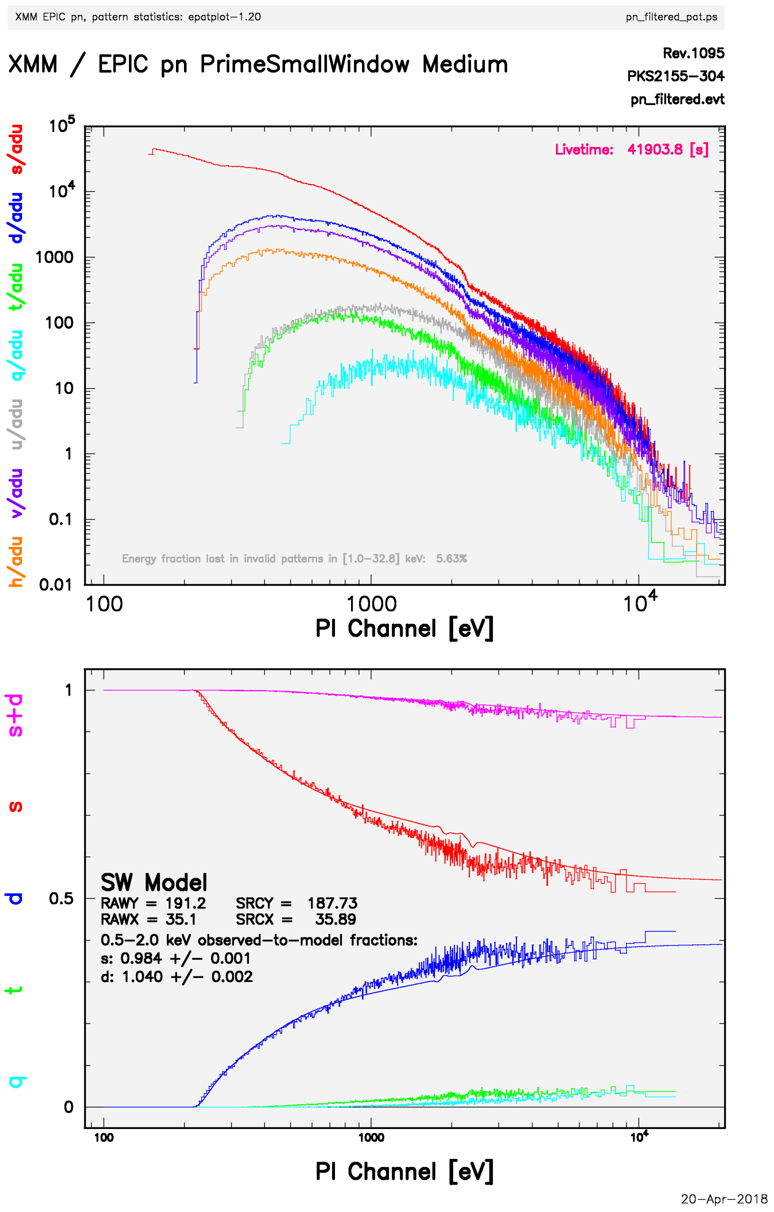


Figure 18: Plot of the pn pattern distribution with energy as produced by epatplot. The deviations of the single, double and single+double distributions from the model are clearly visible.

the xmmselect task, by first displaying the image of the whole source region (see § 4.7) and then defining an annulus (from the ds9:Region menu) which inner radius defines the source region to remove (importing the region into the xmmselect selection expression via the ”2D region” button (see § 4.8.1)). With this selection expression, a filtered event list, named e.g. src_annulus_evlist.fits, can be created with xmmselect. Finally epatplot should be called again now with the src_annulus_evlist.fits as input data set. After inspecting the created pattern distribution curves, the inner radius of the annulus should be increased as long as the pattern distribution agrees with the model. Note that excluding the inner part of the source from the analysis will of course reduce the number of events for further analysis. So an iterative process for finding the best exclusion inner radius should be performed.

One important aspect to be kept in mind, is that excising the core of the PSF on scales too small with respect to the instrumental pixel size (1.1" for the MOS cameras, 4.1" for the PN camera) may introduce systematic inaccuracies in the calculation of the source flux. Simulations show that these systematics are lower than 1% if the radius of the excised core is larger then 5 times the instrumental pixel half-size. For lower sizes these systematics are never larger than 4%. Excising a core, whose size is smaller than the instrumental pixels size, shall be avoided.

Figure 19 shows the pattern distribution of the same source as above, but after exclusion of the inner part of the source. The pattern distributions now agree with the model curves and the resulting spectrum should in principle be free of pile-up effects.

Estimation of the pile-up fraction as a function of pattern, and of the associated flux loss for single events are presented by Ballet (1999) [37]; the treatment is extended to double pixels in Ballet (2003) [38]. Empirical methods to estimate and - partly - correct pile-up based on single-events spectra in the MOS cameras are discussed in Molendi and Sembay (2003) [8].

4.5.1 How to analyse a piled-up Timing mode observation

If a source count rate is greater than $\sim$ 800 counts/s for a pn Timing mode observation or $\sim$ 100 counts/s for MOS Timing mode then the source events are likely to be affected by photon pile-up (Note that in terms of flux, count rates for a given incident flux are higher for soft than for hard spectra; check Section 3.3.9 of the XMM-Newton User Handbook[3] for details).

Users can check if a given EPIC source is affected by pile-up by running the SAS task `epatplot`. Please, refer to the pile-up thread for advise on how to quantify the level of pile-up. A specific caveat applies to EPIC-pn Timing Mode exposures: the source which centroid of it is located at `RAWY=190` or `191` could suffer from a possible systematic offset of a few percent which could be seen when comparing the distributions of observed and expected event shapes (the source position is contained in the keyword `SRCPOS` in the header of the `EVENTS` extension of the event list). The shift is in the positive (negative) direction for single (double) events. This shift is not due to pile-up. It is rather due to residual calibration uncertainties in the pattern fraction distribution as a function of energy in sources close to the first micro-pixel border. The effect is discussed in Guainazzi et al. 2009, CAL-SRN-0265. Users do not need to take any action to correct for this effect, because the calibration of these exposures is nominal.

If a source observed in EPIC fast mode (EPIC-pn Burst/Timing; EPIC-MOS Timing) is affected by pile-up, the boresight column must at least be excised from the region used to accumulate scientific products (this is analogous to removing a circle surrounding the PSF centroid in sources affected by pile-up in imaging modes). If the remaining event list is still affected by pile-up, one must increase the number of excised columns, until the resulting event list is pile-up free.

Users must use the specific procedure outlined below to calculate the effective area associated to a spectrum extracted from a box, from which one or more columns have been excised. The procedure is vald for EPIC-pn and EPIC-MOS. Let us assume that a pile-up free region in a EPIC-MOS Timing Mode exposure is defined by the following `selectlib` expression:

```
( RAWX in [280:298] || RAWX in [303:321] )
```

The BACKSCAL value can be calculated for the created spectrum in the normal manner using `xmmselect` or the `backscale` task. Similarly the tasks `rmfgen` and `arfgen` may be used to create

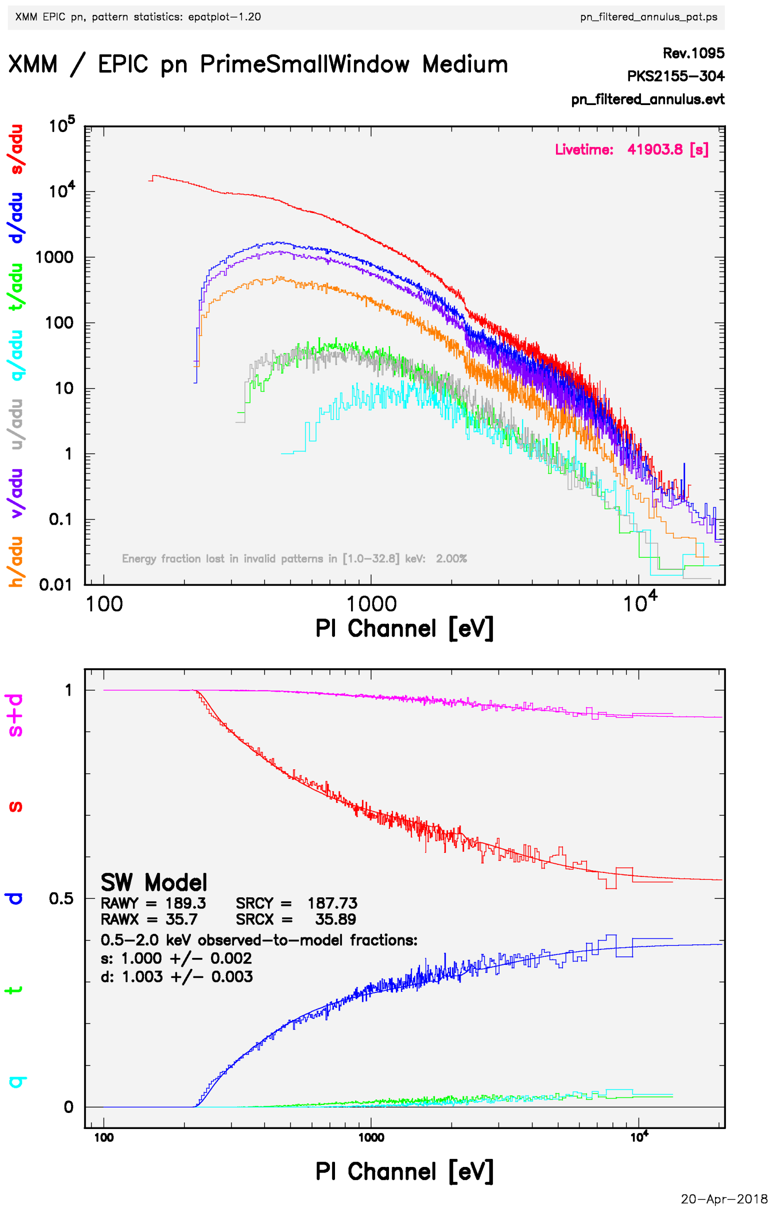


Figure 19: Plot of the pn pattern distribution with energy as produced by `epatplot`. After exclusion of the inner part of the source, the pattern distributions are in agreement with the model curves.

the redistribution matrix (RMF) and ancillary response function (ARF) in the normal manner (see § 4.8.2).

For example, to produce the ARF where the 5 central columns (the boresight plus two columns at each side) are removed:

1. Produce a spectrum (spec_outer.ds)

```
evselect table=EPIC_TimingEvts.ds withspectrumset=yes spectrumset=spec_outer.ds
energycolumn=PI spectralbinsize=5 withspecranges=yes specchannelmin=0 specchannelm
ax=11999 expression='(FLAG==0) && (PATTERN<=0) && ( RAWX in [280:298] ||
RAWX in [304:321] )'
```

2. Produce an ARF

   ```
   arfgen spectrumset=spec_outer.ds arfset=arf_outer.ds detmaptype=psf
   ```

The arf_outer.ds file can then be used as the ARF for fitting the spectrum created from the region:

```
( RAWX in [280:298] || RAWX in [304:321] )
```

together with the RMF produced earlier.

Note: Users working with version earlier than SAS14.0, must use the procedure outlined below to calculate the effective area associated to a spectrum extracted from a box, from which one or more columns have been excised. The calculation of the ARF is a little more complicated because the encircled energy (PSF) correction is not performed correctly by `arfgen` in earlier SAS versions. To overcome this problem the following steps need to be taken.

1. Produce a spectrum (spec_full.ds) from the full area without excluding the central columns, e.g. `( RAWX in [280:321] )`
2. Produce a spectrum (spec_inner.ds) from the excluded region, e.g.

   ```
   ( RAWX in [299:303] )
   ```
3. Produce an ARF for both of these files

   ```
   arfgen spectrumset=spec_full.ds arfset=arf_full.ds detmaptype=psf
   arfgen spectrumset=spec_inner.ds arfset=arf_inner.ds detmaptype=psf
   ```
4. Subtract the inner ARF from the total ARF by using the ftool:

   ```
   addarf "arf_full.ds arf_inner.ds" "1.0 -1.0" arf_outer.ds
   ```

The arf_outer.ds file can then be used as the ARF for fitting the spectrum created from the region:

```
( RAWX in [280:298] || RAWX in [304:321] )
```

together with the RMF produced earlier.

4.5.2 Correcting for the flux loss and energy distortion caused by the pile-up.

The SAS task `rmfgen` includes an option to correct for the flux loss and energy distortion caused by the pile-up of photons within a single frame. It does this by generating a redistribution matrix that attempts to compensate for the pile-up effects, which are calculated from the frequency and spectrum of the incoming photons. Because of this, `rmfgen` needs to read a raw event file to make the pile-up correction. This file should contain all the charges which landed on the CCD where the source is centred. The raw event file is not created by default by the SAS processing. It has to be produced in one of the following ways:

```
epchain keepintermediate=all
```

which produces a raw event file for each CCD with the name `eventsCCD[#].dat`, or,

```
epproc pileuptempfile=yes
```

which produces a raw event file for each CCD with the name `*_CCD[#]_PileupEvts.ds`.

where `[#]` in both cases indicates the CCD number, most commonly `CCD4` where the boresight is located.

The pile-up correction technique used is very compute-intensive, the execution time is of the order of hours for typical observations. This correction technique can only be applied to EPIC-pn imaging modes.

It is also possible at the same time to correct for X-ray loading. The X-ray loading correction is only necessary for EPIC-pn imaging modes. For Timing mode, this is dealt with by SAS automatically, while for MOS, the correction is not necessary.

For this purpose, run the previous commands with options:

```
epchain keepintermediate=all runepxrlcorr=yes
```

```
epproc pileuptempfile=yes runepxrlcorr=yes
```

This produces an output event file with corrected energies.

Once the corrected response file is produced, one can proceed in the usual way. More details are given in the pile-up thread.

4.6 Analysis of extended sources

Analysis of extended sources is complex, challenging and time-consuming. There is currently neither an official SAS recipe, nor a simple thread. The XMM-Newton EPIC Background Working Group (BGWG) was therefore founded in 2005 as a steering and supervising committee to provide the users with clear information on the EPIC Background and (SAS)-tools to treat the background correctly for various scenarios. Although the group stopped its main activities in 2012 the SOC is still responsible for maintaining some of its products.

The progress of the XMM-Newton EPIC Background working group is available at:

http://www.cosmos.esa.int/web/xmm-newton/background

which contains information and tools collected and documented by the Background Working Group during its 7 years of existence. A summary of the contents of these pages is collected below:

- A table summarizing the temporal, spectral and spatial properties of the different EPIC background components.
- Progress and meetings of the XMM-Newton EPIC Background Working Group.
- A list of provided products include:
  - Information on the XMM-Newton Extended Source Analysis Software package for EPIC data, XMM-ESAS, integrated in SAS as of version 9.0.
  - Access to XMM-Newton 'blank sky' background files and related software.

- Access to the Filter Wheel Closed (FWC) repository containing information on the instrumental noise, or Quiescent Particle Background (QPB).
- Links to related papers.

Since SAS v16, it is possible to access the FWC repository through the SAS task `evqpb` to produce a tailored FWC event file suitable for a given science exposure. `evqpb` only deals with EPIC-pn and EPIC-MOS Full Frame mode exposures. Also, as of SAS v19, a new task has been introduced, `qpbselect`, to deal with the QPB in science exposures. `qpbselect` expands the functionality of `evqpb` by using the number of discarded lines (NDISCLIN) to estimate the level of the QPB affecting a given science EPIC exposure. The task will produce a corresponding QPB event file, image and spectrum that can be used to correct the science data. This method is only valid for EPIC-pn, and as of SASv21, applicable only to Full Frame and Extended Full Frame mode data. It is recommended not to use these files for other modes since the instrumental noise depends on the exposure mode used. A dedicated thread explains how to produce and deal with tailored FWC event files to account for the QPB in a given science exposure,

https://www.cosmos.esa.int/web/xmm-newton/sas-thread-background

One of the main problems in the analysis of extended sources is that often no statistically useful blank background region can be defined in the observational field-of-view. A workaround is to make use of the provided 'blank sky' background files to generate background spectra corresponding to the camera/mode/filter combination rescaled to the actual observation.

An alternative approach is to model the background spectra based on the background conditions of the individual observation under study. The recommended method is to make use of the Extended Source Analysis Software (XMM-ESAS) package. As of SAS v9.0, this package is integrated in SAS. The list of XMM-ESAS packages integrated in SAS can be found here:

http://xmm-tools.cosmos.esa.int/external/sas/current/doc/esas/

The XMM-ESAS package allows to model the quiescent particle background both spectrally and spatially for the pn and MOS detectors. XMM-ESAS produces background spectra for user-defined regions of the detectors and background images. As of SAS v21, ESAS has suffered a significant improvement where the ESAS routines have been made less dependent upon the rigid directoryfile name structure of past versions, and have been made more modular. There is an XMM-ESAS Cookbook [39] and three SAS Analysis Threads that describe how to use XMM-ESAS step-by-step.

A description of how to use an image from another instrument to correct for flux lost in an extended image, due to chip gaps and bad pixels, is given in the `arfgen` user guide and in the Technical Note CAL-TN-0227.

Suggestions and caveats on the analysis of extended sources with the EPIC cameras have also been addressed in a SAS workshop presentation (available from the SAS Workshop page).

4.7 Generating EPIC images

EPIC images can be created from an event file with the `evselect` task from the command line or with the `xmmselect` task in an interactive GUI driven way.

4.7.1 Image generation with `evselect`

The task `evselect` creates a simple output image file in the following way:

```
evselect table=inevlist.fits xcolumn=X ycolumn=Y imagebinning=binSize \
         ximagebinsize=100 yimagebinsize=100 \
         withimageset=true imageset=image.fits
```

where `table` specifies the input event list, `x/ycolumn` the coordinates used for the image (here sky coordinates), `imagebinning` is a switch for an automatic or user defined binsize, `x/yimagebinsize` is the user defined bin size of the image in each direction, `withimageset` is the switch to create an image and `imageset` defines the name of the output image file. In this example the bin size is set to 100 which corresponds in the sky pixel system (units are 0.05 arcsec) to 5 arcsec.

4.7.2 Image generation with `xmmselect`

An alternative (and more interactive) approach is to create images via the `xmmselect` GUI, which is started with the command:

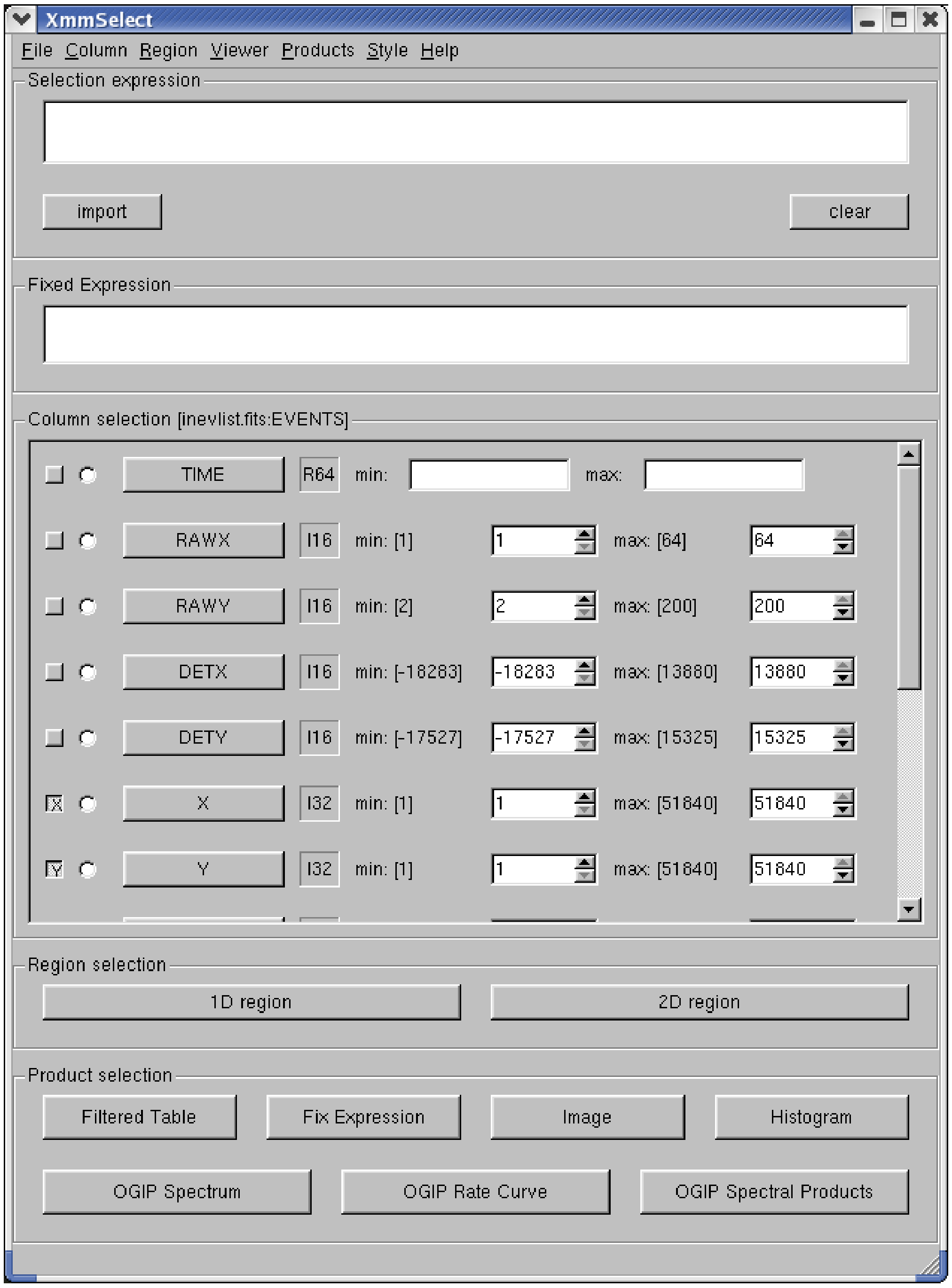
```
xmmselect table=inevlist.fits
```

Afterwards, the following steps need to be performed to generate and display an EPIC image:

1. Choose X and Y in the Column selection (input columns for the image, e.g. X and Y (sky coordinates), RAWX and RAWY (raw CCD-specific coordinates) or DETX and DETY (camera-specific coordinates) and click in the Product selection part on the "Image" tab (see figure 20). This will start the general window of the `evselect` task.

   Caution: if `x/ycolumn` in `evselect` are the CCD raw coordinates RAWX and RAWY, all selected CCDs will be projected on top of each other. If an image in RAWX and RAWY is needed e.g. for diagnostic purposes, an additional filter expression selecting a single CCD only should be applied. In order to get an image of all active CCDs in the camera, the `x/ycolumn` should be set to X and Y or DETX and DETY.

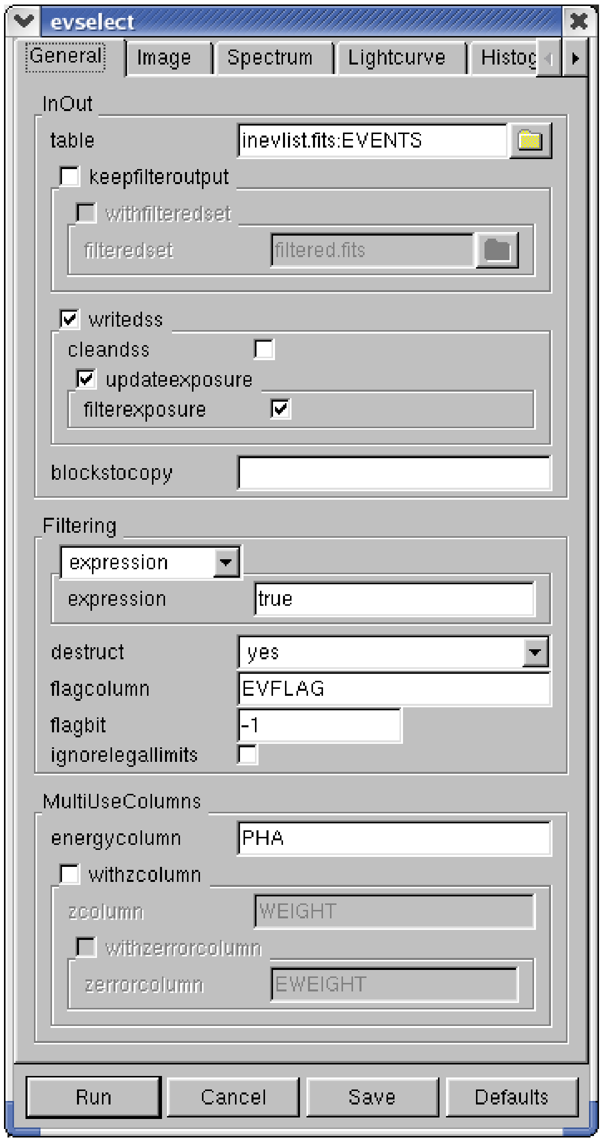
2. In the `evselect` main window (figure 21) one now has the option to apply further events filtering (if not yet specified in the `xmmselect` main window). If one is happy with the set-up, the next step is to click on the "Image" button on the top of the GUI.



☐	TIME	R64	min:		max:	
☐	RAWX	I16	min: [1]	1	max: [64]	64
☐	RAWY	I16	min: [2]	2	max: [200]	200
☐	DETX	I16	min: [-18283]	-18283	max: [13880]	13880
☐	DETY	I16	min: [-17527]	-17527	max: [15325]	15325
X	X	I32	min: [1]	1	max: [51840]	51840
Y	Y	I32	min: [1]	1	max: [51840]	51840

Figure 20: In the `xmmselect` main window, an image can be extracted by selecting X/Y as image axis and by pressing the ”Image” button.

3. In the now visible `evselect` window with the image creation related parameters (figure 22) one needs to specify a name for the output image (parameter `imageset`). By default, events will be binned into an image with 600 x 600 square pixels. The image size can be modified as well as the binning mode: setting `Binning` to `binSize` allows e.g. to project events onto a grid with specified pixelsize (a value of `x/yimagebinsize`=100, e.g. will result in 5 x 5 arcsec pixels).



InOut

table: inevlist.fits:EVENTS
[ ] keepfilteroutput
[ ] withfilteredset
filteredset: filtered.fits
[✓] writedss
cleandss: [ ]
[✓] updateexposure
filterexposure: [✓]
blockstocopy:

Filtering

expression
expression: true
destruct: yes
flagcolumn: EVFLAG
flagbit: -1
ignorelegallimits: [ ]

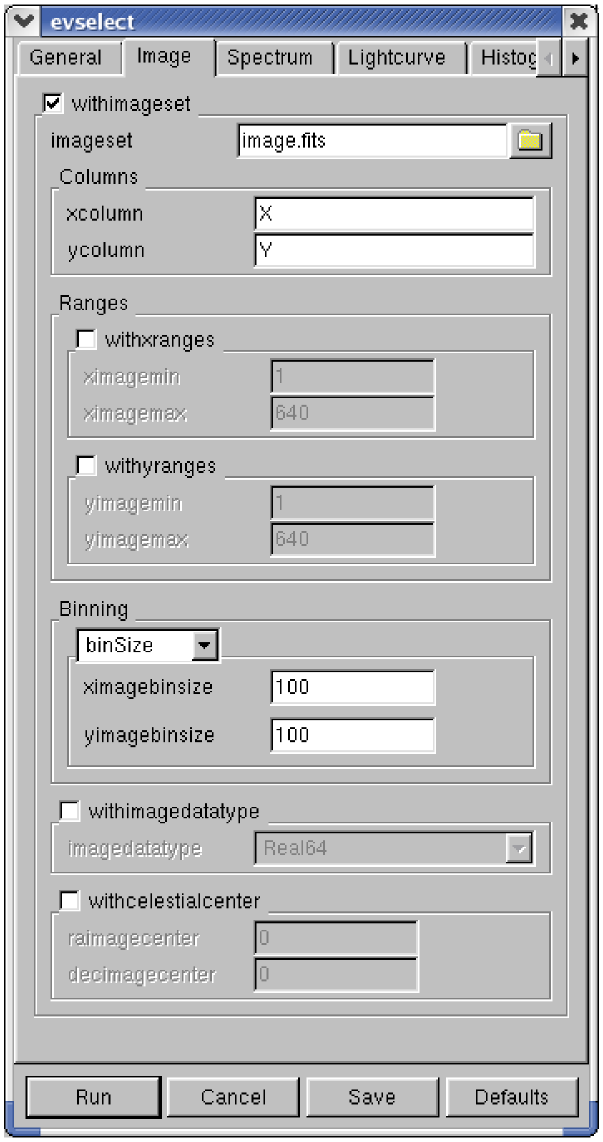
MultiUseColumns

energycolumn: PHA
[ ] withzcolumn
zcolumn: WEIGHT
[ ] withzerrorcolumn
zerrorcolumn: EWEIGHT

Figure 21: The `evselect` main window, where e.g. the selection expression still can be modified.

4. Click on the "Run" button to start the image creation process. After the image is created and stored in the working directory, `xmmselect` will automatically launch the image viewer. The `ds9` viewer allows the user to zoom in on a region of special interest, to change the intensity scale and the color. The position of the mouse pointer is displayed (in RA and Dec in case of a sky image, or in linear coordinates in case of a camera or raw coordinate image). For details on the image viewer (developed by Smithsonian Astrophysical Observatory), follow the links to further information that are available under the `ds9` "Help" button.

Note, if running the image creation for a second time with the same name for the output image (parameter `imageset`), the previously created image file will be overwritten. This can be avoided by starting `xmmselect` with the "-c" (no clobber) option (see documentation of the `taskmain` SAS package).



withimageset	✓
imageset	image.fits
xcolumn	X
ycolumn	Y
withxranges	
ximagemin	1
ximagemax	640
withyranges	
yimagemin	1
yimagemax	640
Binning	binSize
ximagebinsize	100
yimagebinsize	100
withimagedatatype	
imagedatatype	Real64
withcelestialcenter	
raimagecenter	0
decimagecenter	0

Figure 22: The `evselect` window with the image related parameters, where e.g. the output image name and the binning of the events can be modified.

4.7.3 Image generation with `etruecolor`

The task `etruecolor` generates from a set of input event list (for EPIC MOS, EPIC pn or a combination of both) a spatial image in which the value of the scalar event attribute `energy` is three-color coded. The actual generation of the red, green, and blue component images is done through the task `evselect` (see § 4.7.1), where `etruecolor` filters the input table using the `min` and `max` parameter assigning each energy value a color index. More information on the task `etruecolor` can be found on the online SAS documentation on individual SAS tasks.

An example is given below as to how this task works. This example combines images of the three EPIC cameras in the energy range between 3 and 7 keV.

```
etruecolor tablelist='pn_evfile mos1_evtfile mos2_evtfile' attfile=AttHk.ds \
     min=300 max=7000 fileset='MY_COLOR_IMAGE.FIT'
```

where pn_evfile, mos1_evtfile and mos2_evtfile are filtered event files corresponding to the three EPIC instruments, and min and max the explicit minimum and maximum values respectively for the energy in eV. AttHk.ds is the attitude history file generated by the SAS task attcalc (automatically produced by epproc and emproc, or epchain and emchain). The energy bands for the red, green and blue channels of the true color image have been chosen so that a power law spectrum with photon spectral index 1.7, absorbed by galactic gas with neutral hydrogen column density of 10^{20} cm^{-2}, results in approximately the same number of counts in each band.

The output of this particular example is a data set containing three arrays with R/G/B components respectively, which can be viewed by the image viewer ds9 [27], version 2.3 or later, by typing:

```
ds9 -rgbcube MY_COLOR_IMAGE.FIT
```

Figure 23 shows the resultant three color coded images (red, green and blue) and the combined image.

4.7.4 Image generation with eimageget

The task eimageget generates EPIC vignetting-corrected background-subtracted images. The task only works on EPIC-pn Full Frame and Extended Full Frame mode and EPIC-MOS Full Frame mode exposures.

For a given science exposure the task generates the following set of files (Fig.24):

```
    Pobsid[PNpid,M1m1id,M2m2id]_ima_[0-4].fits     ; science exposure images
    PobsidPNpid_ima_[0-4]oot.fits                  ; Out-of-Time exposure
                                                     images (only for PN)
    Pobsid[PNpid,M1m1id,M2m2id]_ima_[0-4]fwc.fits  ; Filter Wheel Close
                                                     exposure images
    Pobsid[PNpid,M1m1id,M2m2id]_ima_[0-4]exp.fits  ; Exposure maps
    Pobsid[PNpid,M1m1id,M2m2id]_ima_mask.fits      ; A single mask valid
                                                       for all energy bands
```

where *obsid* indicates the observation id and *pid*, *m1id* and *m2id* the ids of the EPIC-pn, EPIC-MOS1 and EPIC-MOS2 exposures respectively. The Out-of-Time event file is only generated for the case of EPIC-pn. [0-4] indicates the different energy ranges which can be controlled via task parameters, by default:

```
       0: 0.2-0.5 keV
       1: 0.5-1.0 keV
       2: 1.0-2.0 keV
       3: 2.0-4.5 keV
       4: 4.5-12.0 keV
```

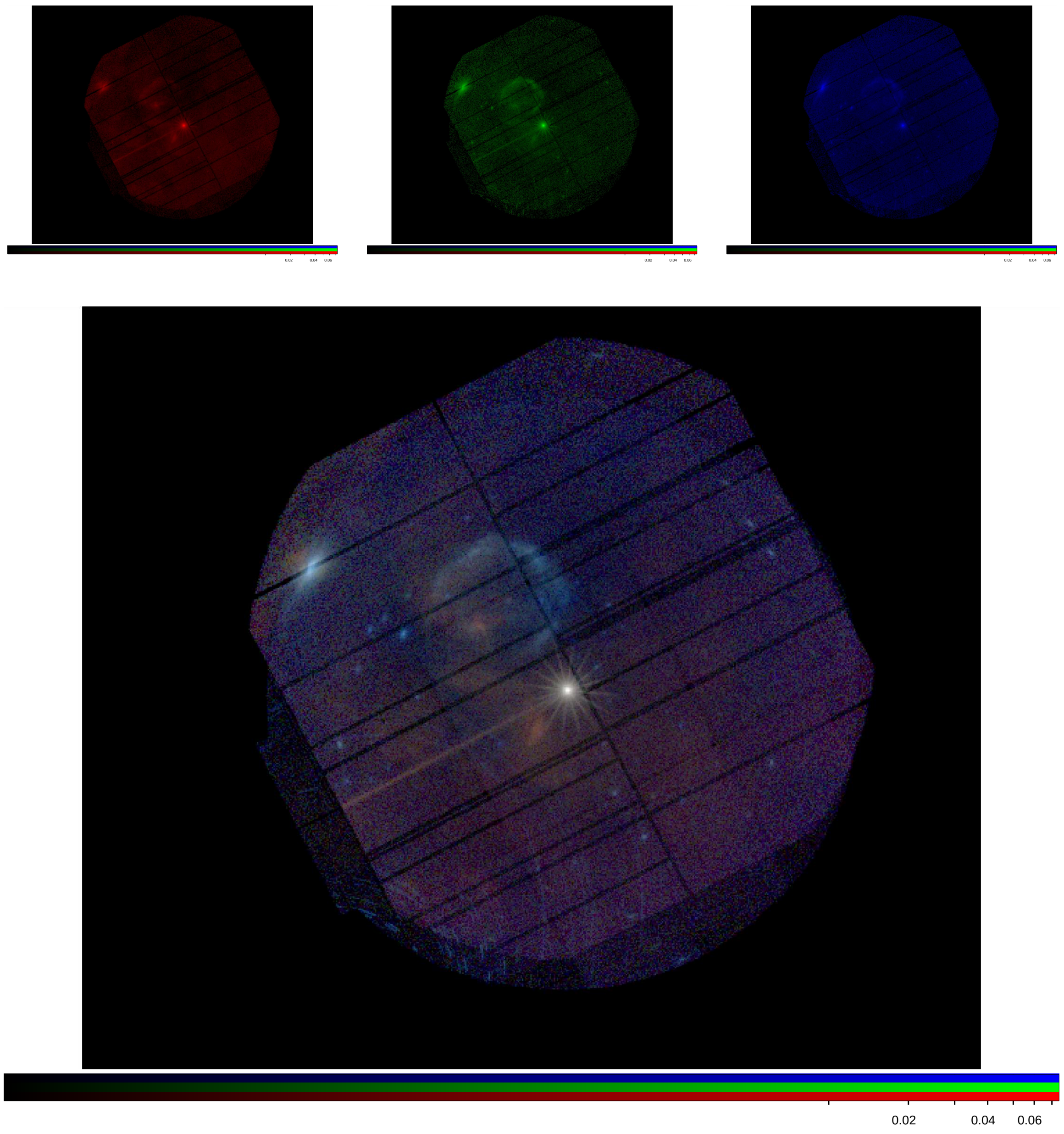


Figure 23: Three color-coded EPIC image produced by the SAS task `etruecolor`. Top, from left to right, red, green and blue images. Bottom, combined color-coded EPIC image.

The task `eimagecombine` can be used to conveniently combine the individual output images of `eimageget` to produce background-subtracted, vignetting-corrected, and smoothed image of EPIC exposures (Fig.24).

A dedicated SAS thread explains the detailed steps needed,

https://www.cosmos.esa.int/web/xmm-newton/sas-thread-images

4.7.5 Image generation with the *images* script

The *images* script is a tool designed to create attractive XMM-Newton images. *images* is a bash shell script designed to reduce and combine data from the XMM-Newton EPIC pn and MOS cameras to produce X-ray images in several energy bands. OM data processing is also performed if required. The script performs several corrections to the data including, filtering for periods of high background, removal of bad pixels and columns (from calibration files and user-specified), smoothing, exposure correction, and merging of pn and MOS data. The script, along with information on how to use it, can be found at:

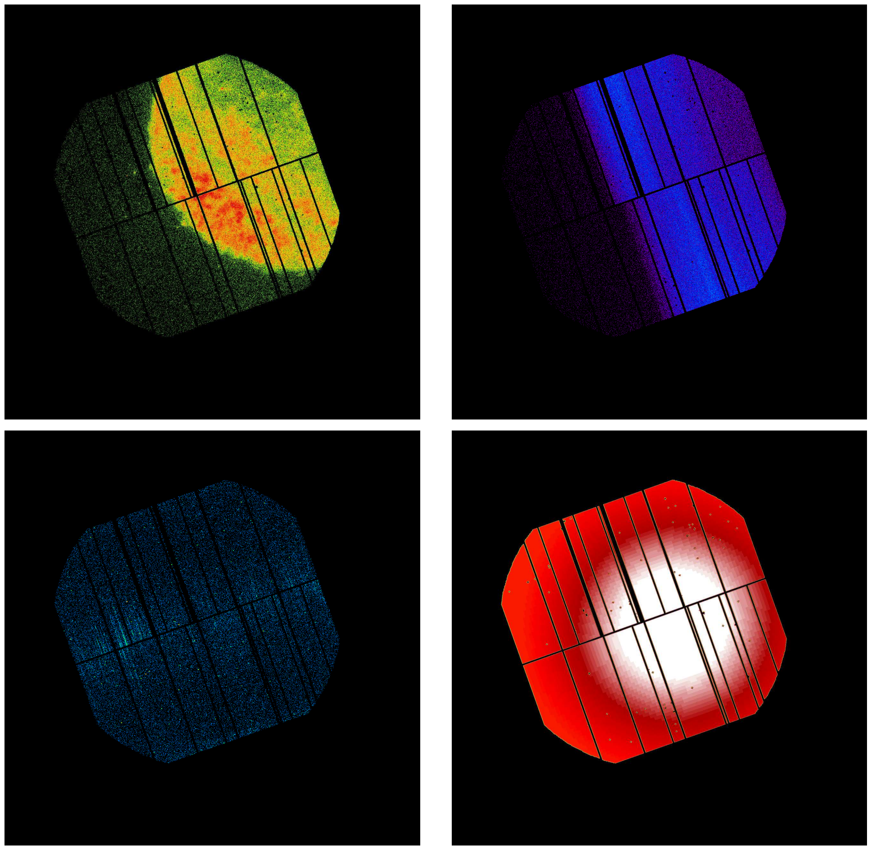
http://www.cosmos.esa.int/web/xmm-newton/images

4.7.6 Analysing EPIC images

There are a set of routines in SAS which are useful for processing regions within images. These routines return information which can be used for further processing.

- `eregionanalyse`: Given an EPIC image, this task performs a source region optimization. The image should be in detector or sky (X/Y) coordinates, like standard images produced by `evselect` or `xmmselect` and the pipeline. Spatial regions may be entered in detector, sky (X/Y) or celestial (RA, DEC, FK4 2000) coordinates. `eregionanalyse` returns amongst other information, source centroid, optimum extraction radius, source counts, count rate, etc... All these values are written to standard output.
- `psfgen`: This task generates the point spread function from a calibration file provided an EPIC image or a defined region within the image.
- `eradial`: Is a task that allows to extract a radial profile of a source in an EPIC image from the field of view of an observation and compare it with the nominal point spread function from a calibration file. This allows to test whether a source is extended or not by inspecting the provided output; the radial profile, the theoretical point spread function at that position in the image and at that energy, and the best fit normalisation of that PSF to the actual radial profile data.

More information on these tasks can be found at the SAS tasks documentation web pages.



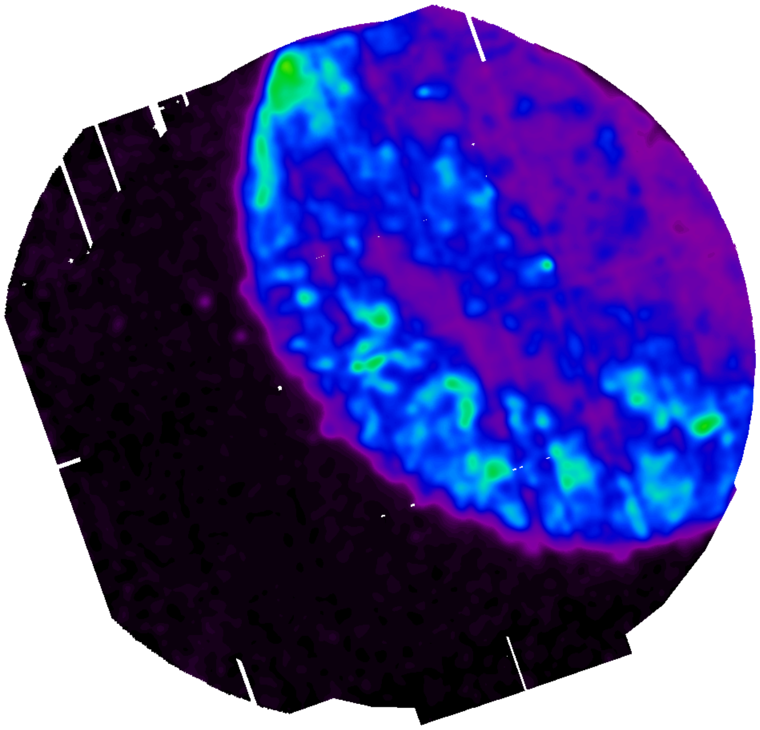


Figure 24: The result of applying `imageget` to the EPIC-pn science exposure. Images correspond to the lowest energy range, 0.2-0.5 keV. From top lef to bottom right; science exposure image, scaled Out-of-Time exposure image, scaled Filter Wheel Close exposure image, and exposure

4.8 EPIC spectral analysis

4.8.1 Generating spectra

EPIC calibrated event lists must be filtered to generate spectra. As for images, this filtering is normally performed in two steps. First, the event lists are screened to reject spurious data and to select only events which contain information of sufficient quality for further scientific analysis. Secondly, the screened data are filtered to construct data subsets adapted to specific spectral analysis.

For the latest information on general recommendations for a conservative spectral analysis (i.e. recommendations about where the data should be taken from the CCD, which energy and pattern range should be used, which event quality flags should be selected), the user is strongly advised to check the related sections in document "EPIC status of calibration and data analysis" (XMM-SOC-CAL-TN-0018, [12]), available on the XMM-Newton SOC Calibration Web page at http://www.cosmos.esa.int/web/xmm-newton/calibration.

See also the SAS threads at:

http://www.cosmos.esa.int/web/xmm-newton/sas-threads

The screening and filtering activities can be performed in an interactive manner with the SAS task `xmmselect`. Basically, there are two possible approaches offered by `xmmselect` to generate EPIC spectral products:

- generate source and background spectra separately via the `xmmselect` product selection "OGIP Spectrum". This approach requires more analysis steps but is described here as users might be interested in details,
- generate source and background spectra (together with related response files) with the meta-task `especget` called via the `xmmselect` product selection "OGIP Spectral Products".

For both cases, an EPIC image must be created and displayed with `xmmselect` running on a filtered (or the original) event list (see § 4.7.2). Note that it is not enough to display an image through `ds9` for `xmmselect` to be able to communicate with it, the `ds9` window must have been launched by `xmmselect`.

In the following, the analysis steps for the "OGIP Spectrum" approach are described:

1. In the `ds9` window, create a region for the source of interest. Click once on the `ds9` image and a region circle will appear (other region shapes are available as well). Click on the region circle and the region will be activated, allowing the region to be moved and its size to be changed. Having created, placed, and sized the region appropriate for the source, click the "2D region" button in the `xmmselect` GUI. This transfers the region information into the "Selection expression" text area in `xmmselect`. A newly defined `ds9` region file can optionally be saved to disk via the `ds9` "Region" → "Save Regions..." menu and re-loaded for further analysis steps via the "Region" → "Load Regions..." option.

   Note: For pn data of bright sources and of sources with narrow lines it might be good to extract two spectra and corresponding backgrounds, response and ancillary files: one set for single pixel events (`PATTERN==0`) and another set for doubles (`PATTERN IN [1:4]`). Fitting these two spectra simultaneously will show if there are any problems with pile-up (see § 4.5) and - as the energy calibration for singles is slightly better than the one for doubles - will show the line features at highest energy resolution in the single events spectra.

2. To extract the spectrum, first click the circular button next to the PI column in the `xmmselect` GUI. Next click the "OGIP Spectrum" button. Select the "Spectrum" page of the `evselect` GUI to set the file name and binning parameters for the spectrum. For example, set `spectrumset` to `src_spectrum.fits`. The parameter `spectralbinsize` (the size of each spectral bin in instrumental eV) shall be set to the same value (e.g., 5), if the user wishes to merge the EPIC -MOS and -pn spectra into a single EPIC spectrum (see the "Combining the spectra of the 3 EPIC cameras" thread;
`http://www.cosmos.esa.int/web/xmm-newton/sas-threads`).
Otherwise, the user is free to choose the bin size independently for each camera. `withspecranges` must be checked, `specchannelmin` set to 0, and `specchannelmax` set to 11999 for the MOS or 20479 for the pn. Figure 25 shows a plot of an example output spectrum which is automatically displayed in a `grace` window upon generation by `xmmselect`.

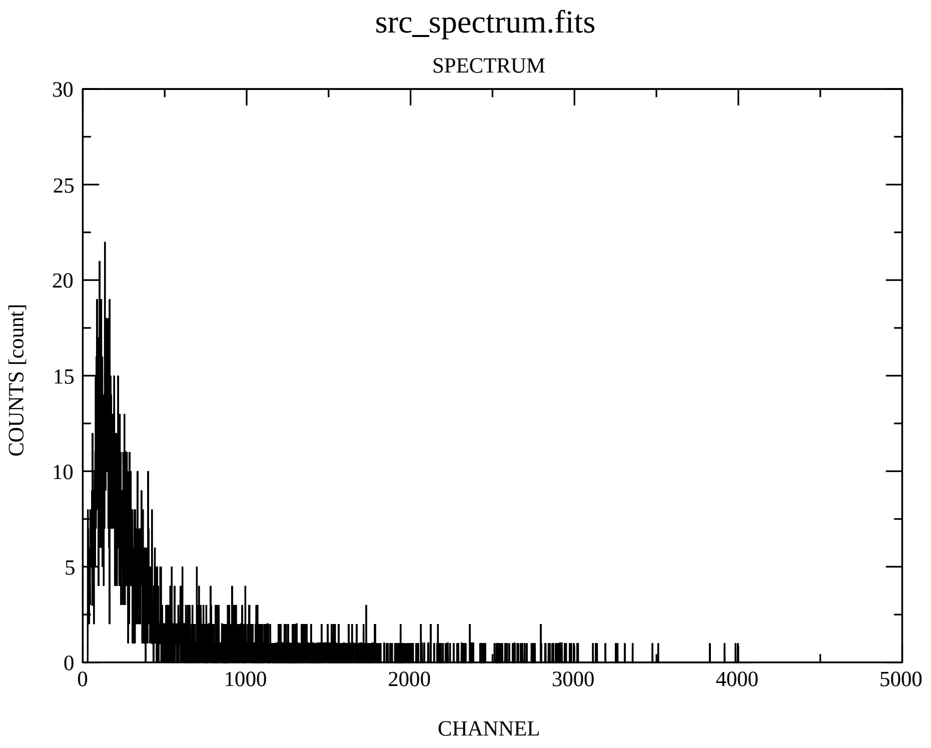


Figure 25: Example of count spectrum of a source which is automatically displayed in a `grace` window upon generation by `xmmselect`.

Note: `xmmselect` performs the calculation of the `BACKSCAL` factor, which takes into account CCD gaps, bad pixels and the size of the extraction region, on the fly during the spectrum generation. If `evselect` is used instead for the extraction of the source and background spectra, the `BACKSCAL` factor must be calculated explicitly by executing the `backscale` task before any subsequent quantitative analysis, e.g. with `Xspec`, can be performed.

3. For checking whether pileup (§ 4.5) might be a problem, create a source event file by checking the `keepfilteroutput` and `withfilteredset` boxes on the `evselect` "General" page and provide a `filteredset` name, e.g. `src_evlist.fits`, for the resultant file. For this event file, remove the `&&(PATTERN<=4)` phrase for the pn so that single, double, triple, and quadruple events are all included. This filtered event list should be used as input file for the pattern analysis to be performed by `epatplot` (see § 4.5).

4. To extract a background spectrum from a source-free area, first remove the spatial selection (previously defined for the source) from the "Selection expression" window in `xmmselect`. Next repeat step 1) except using now the "Region" option of `ds9` to define the background area and then click the "2D region" button. This will transfer the background region description to the "Selection expression" in `xmmselect`. Finally, repeat step 2) except setting now the `spectrumset` parameter to a different file name, e.g. `bkg_spectrum.fits`.

   Note: Background extraction from a source-free area might be a problem in case of crowded fields. As a general advice for MOS, the source-free background region should be extracted at roughly the same off-axis angle as the position of the source. For pn, the recommendation is to select a source-free background region at the same RAWY position on the chip as the source (RAWY being the long axis of the CCD). So if the pn source is located e.g. at RAWY line 150 on CCD 4, one should aim for selecting the background from around line 150 on the same chip or, at least, from a chip belonging to the same quadrant.

In the case of **extended sources**, where virtually no emission free regions exist on the CCD, the user is advised to make use of EPIC background files and tools available through the SOC pages (further details are given in § 4.6). An alternative approach for MOS might be to extract source-free background regions from the outer CCDs (which always are collecting data in imaging mode).

In the case of EPIC **timing** and **pn burst** mode observations that generally are performed for bright point-like sources, the background will usually not be an issue. Note that in these modes, the RAWY coordinate is not giving spatial but timing information and the source is visible as a bright strip when plotting RAWX against RAWY. In the case of the MOS cameras, the timing strip is only 100 pixels wide and if a background spectrum needs to be extracted it should be taken from the outer CCDs which are collecting data in imaging mode. In the case of the pn, background regions can be extracted in emission-free strips parallel to the readout direction (i.e. defining a spatial filter expression in RAWX only - a selection in RAWY would incorrectly exclude certain time intervals) excluding the region with registered events from the source.

Details on how to extract source and background regions for the case of EPIC **timing** mode are given at:

http://www.cosmos.esa.int/web/xmm-newton/sas-threads for the case of pn and MOS.

For the analysis of **pn burst mode** data special care has to be taken in the way of selecting the source and background regions. RAWY may have to be chopped in order to exclude contamination from the source, see e.g. the analysis of burst mode data of the Crab in Kirsch et al. (2006) [10], section 3, available online as XMM-SOC-CAL-TN-0069 [10].

Some information on the analysis of extended objects, particularly where a determination of the background is difficult from the individual data set, is provided in § 4.6.

4.8.2 Creating response matrices

Analysis of EPIC data products is generally performed by specialised software packages including `Xspec`[28], `Ximage`[16] or `Xronos`[15] (http://heasarc.gsfc.nasa.gov/docs/xanadu/xanadu.html). In addition to the calibrated products, some of these packages require the generation of specific files. In particular, the spectral fitting technique used by `Xspec` requires a characterization of the EPIC detector response to simulate an output spectrum observed by EPIC. The response function gives the probability that an incoming photon of energy E will be detected in a channel I. This discrete function can be calculated as a product of a Redistribution Matrix File (RMF) by an Auxiliary Response File (ARF). These response files shield the user from the complexity of the EPIC instrument response which varies across the field of view.

There are currently two approaches to obtain RMF redistribution matrix files:

1. The user can make use of ready made (canned) response matrices made available by the EPIC team and accessible through the EPIC Response Files page at

   http://www.cosmos.esa.int/web/xmm-newton/epic-response-files

   They are virtually identical to the files produced by the SAS task `rmfgen`.

   Special care must be taken in choosing the appropriate canned RMFs as they depend on the readout mode, the pattern selection, the observation date and the position of the source.

2. The user can also create the RMF using the `rmfgen` task (`rmfgen` might take some time to complete, depending on the hardware). The input spectrum file contains the necessary ancillary information to allow the correct response to be made. It corrects for instrumental effects specific to the spectrum and writes the result to a specified dataset.

The RMFs are spatially dependent for both MOS and pn. If source extraction regions are large, e.g. for extended sources, timing mode data or complex regions containing many excluded sources, it is important to specify an appropriate number of detector map bins to allow the SAS to calculate an average response matrix (also see § 4.8.6). It is recommended to use 160 bins in each dimension by:

```
rmfgen spectrumset=<spectrum_file> rmfset=<rmf_file> detxbins=160 detybins=160
```

The ARF response file of the EPIC camera shall then be generated by the task `arfgen`. This task calculates an effective area curve as a function of energy, to be used in conjunction with the RMF file generated before. For each row of the RMF there is a corresponding element in the 1-D ARF. This is normally adjusted by specifying the previously generated response matrix as an input file to the `arfgen` task.

The `arfgen` task generates an ARF file taking into account the following effects:

1. Telescope effective area including vignetting by the RGA structure for the MOS cameras,
2. EPIC filter transmission,
3. EPIC CCD quantum efficiency,
4. Region and pattern selections,
5. Fraction of the PSF in the accumulation region (including chip gap, bad pixel and out of observing window effects),
6. Out-of-time events smearing (pn).

The above effects generally depend on the source position in the EPIC field of view. Spatial response variation over an extended source is also taken into account (see § 4.8.6).

As of SAS v12, a full 2-D parameterisation of the PSF as a function of camera, energy and off-axis angle covering the whole field of view is available as the default mode. A full description of the PSF modeling is available at [40]. The 2-D PSF parameters are included in the ELLBETA extension of the PSF CCFs. ELLBETA supersedes all previous PSF models used so far. Users can still access the parametrization of old models through calview, which reads the corresponding extensions of the PSF CCF constituent, or by selecting the appropriate value in the input parameters of those tasks (e.g., `arfgen` through its input parameter `psfmodel`), which make use of the PSF.

As of SAS v20.0 a new parameter for `arfgen` is available, `applyfluxcorr` which, when set to `yes`, will correct the EPIC effective areas to be in better agreement with the absolute flux measurements provided by NuSTAR. Using this correction will result in a reduction of the EPIC effective area by about ∼18% over the whole energy range. However, as of the release of this guide, the corresponding CCF files are not yet available and the parameter is non-functional. Please watch for an upcoming CCF release of the XRT3_XAREAEF file, which will include the corresponding information.

4.8.3 Generating source and background spectra in one go

The following section shows an alternative approach to generate source and background spectra in a single step (optionally together with related response matrices - see § 4.8.2): the `xmmselect` product selection "OGIP Spectral Products" starts the meta-task `especget` which is a one-stop task producing all the files necessary for the spectral fitting of an XMM-Newton source. `especget` runs the tasks `evselect`, `arfgen` and `rmfgen`. It also calculates the size of the source and background areas by calling `backscale`. The end result is a set of files which can be used directly in a spectral fitting programme like e.g. `Xspec`.

The interactive steps needed during the "OGIP Spectral Products" approach (assuming that an EPIC image was created with `xmmselect`) are listed below:

1. In the `ds9` window, create a region for the source of interest. Click once on the `ds9` image and a region circle (default shape) will appear. Click on the region circle and the region will be activated, allowing the region to be moved and its size to be changed. Having created, placed, and sized the region appropriate for the source, one needs to define a region from which to extract the background: this is done in a similar way as before for the source region, but now this second region must be placed in a source-free area (see recommendations on where to place the background region given earlier in this section). Click on the background region and modify its position and size. Via the `ds9` "Region" → "Properties" menu the region types must be defined as "Source" for the source and "Background" for the background region, respectively.

2. Start the spectral product generation by clicking on the "OGIP Spectral Products" product selection in `xmmselect` (cf. figure 20). The task `eregionanalyse` performs a source region optimization and the optimized source region is shown in the `ds9` window, the proposed region parameters are given in a popped-up window and the user is asked to confirm if the optimized or the original region should be used for further analysis (or if the spectral product generation is aborted at this stage).

3. If a source region is accepted, the `especget` GUI appears and shows the corresponding spatial selections for the source (parameter `srcexp`) and background (parameter `backexp`) regions (figure 26). The user might want to modify the stem for the output filenames (parameter `filestem` on "filenames" related parameter page). For extended sources, the parameter `extendedsource` (on the "effects" related parameter pages) should be set to true. Pressing the "Run" button of the GUI starts the generation of source and background spectra (and response matrices). The meta-task `especget` finishes the processing displaying the generated source spectrum.

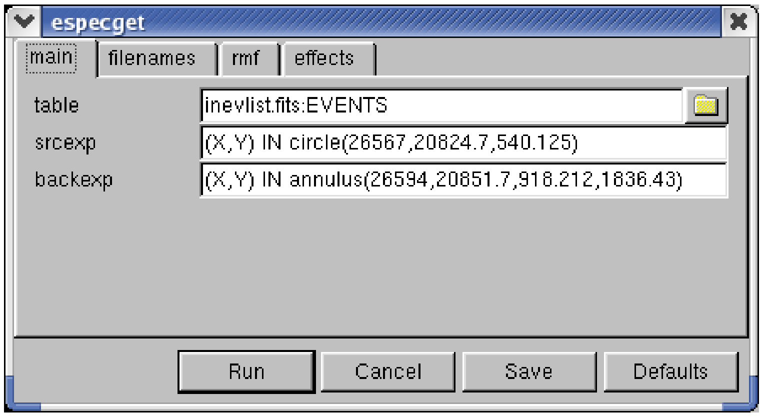


table	inevlist.fits:EVENTS
srcexp	(X,Y) IN circle(26567,20824.7,540.125)
backexp	(X,Y) IN annulus(26594,20851.7,918.212,1836.43)

Figure 26: GUI of `especget` showing source and background spatial selection expressions.

Once all the spectral products are available, the SAS task `specgroup` allows further processing of the spectral files by performing a user-defined grouping of channels in the spectrum. The task also links the associated files by adding the information to the header of the source spectral file, useful for example when working with the software package `Xspec`[28]. The grouping of the spectrum can be done in several ways (see the description of the task for information on grouping options) included grouping based on minimum number of counts per channel, and several based on statistical criteria.

Note: `especget` writes the names of the created files into the source spectrum header keywords BACKFILE, RESPFILE, ANCRFILE. These may be automatically read by spectral fitting programmes to link the files and perform area weighted background subtraction. `especget` applies the following default event selections, for pn `'(FLAG==0) && (PATTERN<=4)'` and for MOS `'#XMMEA_EM && (PATTERN<=12)'`. `especget` also takes care of the different spectral ranges and binnings for pn and MOS spectra that need to be applied.

4.8.4 Generating spectra from RGS multi-pointing mode data

In an observation that has been taken in RGS multi-pointing mode, the position of the source on the EPIC detector changes with each exposure (typically the shift between exposures is 15 or 30 arcseconds). This is illustrated in Figure 27.

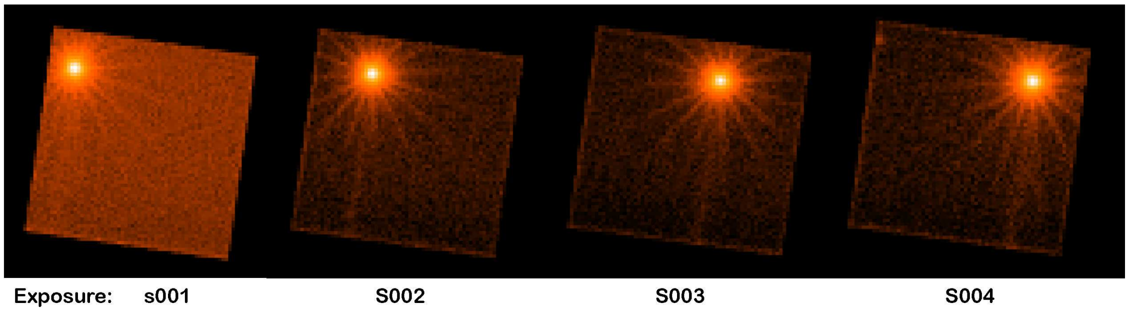


Figure 27: Example of a source observed in RGS multi-pointing mode in the EPIC-pn small window.

In order to analyse the EPIC data gathered under the RGS multi-pointing mode, SAS needs to know the satellite pointing in each exposure. The procedure to analyse EPIC-pn or EPIC-MOS data changes slightly, mainly, in the way event files for each sub-pointing are derived. Once event files exist for each sub-pointing and EPIC camera, the task `arfgen` needs to be able to handle the different sub-pointings. This is done by using the attitude history file. In particular, the task `arfgen`, needs to convert from sky coordinates into detector coordinates by using this file, which is achieved by setting the task parameter `useodfatt=yes`.

Details on how to proceed in order to analyse EPIC data under the RGS multi-pointing mode can be found in a dedicated thread: https://www.cosmos.esa.int/web/xmm-newton/sas-thread-epic-spectrum)

4.8.5 Spectral products for overlapping EPIC data

From SAS v13.0 onwards, the combination of data from overlapping fields observed repeatedly by XMM-Newton is possible, either to obtain a larger signal to noise ratio for a given source or to check for variability.

The tasks `xmmselect` and `especget` have been adapted to work with several exposures at once, making the work to be performed in the case of overlapping fields easier. The equivalent multiexposure tasks area called `multixmmselect` and `multiespecget`. `multixmmselect` starts a graphical user interface which allows the user to work with several event files from different input exposures simultaneously. Since `multixmmselect` handles at the same time event files from EPIC MOS and pn, as opposed to the `xmmselect` task, it only includes a subset of filtering parameters. A key feature of `multixmmselect` is the ability to extract spectra by selecting a common extraction region to all the single exposures at once. This is done through `multiespecget`, a modified version of `especget` for single exposures. Even further, it is possible, by selecting the appropriate parameter in `multiespecget`, to get as a result of running this task, to obtain a combined spectra and matrices including all the individual exposures. This is done through the use of the task `epicspeccombine`.

All the described functionality can be accessed in a simple way from the `multixmmselect` graphical user interface. `multixmmselect` also offers the possibility to obtain single exposure light curves and combined images in one single easy step. A SAS thread (Overlapping EPIC data treatment) describes in detail how to perform the described analysis.

4.8.6 Response files for extended sources

In this section, general recommendations for the generation of the appropriate redistribution matrix and auxiliary response file for extended sources are given.

As the response function of the EPIC cameras is spatially dependent, the `rmfgen` and `arfgen` tasks need to know how the source flux is distributed within the extraction region. A detector map mechanism, has been adopted for this purpose. Essentially a grid is placed over the source region and the response parameters are calculated at each point and then averaged taking into account the flux distribution. For point sources the flux distribution is that of the point spread function (default setting `detmaptype=psf`).

Large, non point-like sources should be either approximated by a uniform distribution, setting `detmaptype=flat`, or modeled accurately by creating an image of the source region. Such a detector map can be created using `evselect` or `xmmselect` (see § 4.7). The detector map should entirely cover the region used for extracting the spectrum and should be created with sufficient resolution to sample the variation in flux distribution; a 100 by 100 pixel image may be sufficient. The detector map is supplied to the `rmfgen` and `arfgen` tasks by setting

```
rmfgen spectrumset=<spectrum_name> rmfset=<rmf_name> detmaptype=dataset \
       detmaparray=<detector-map_name>
```

and

```
arfgen spectrumset=<spectrum_name> arfset=<arf_name> detmaptype=dataset \
       detmaparray=<detector-map_name> extendedsource=yes
```

The task descriptions give further info and provide some examples for the generation of response matrices for extended sources.

4.8.7 Use of `efluxer`

`efluxer` converts an X-ray EPIC spectrum generated by `evselect/xmmselect` from the usual counts versus instrument channels space into physical units (i.e. flux density versus energy). The algorithm corrects for the energy redistribution and the effective area of the telescope, for any combination of scientific modes and filters. The output produced as a result of running this task is a FITS file containing the fluxed spectrum, which includes the columns, FLUX, ERROR, ENERGY, ENERGY_BIN. Figure 28 gives two examples to illustrates the results obtained by the use of the `efluxer` task.

The algorithm used by `efluxer` inherently degrades the spectral energy resolution with respect to the intrinsic instrumental one. Therefore, users are advised to use the EPIC fluxed spectra to obtain model independent fluxes in broad energy bands or in analysis of continuum shapes or for quick-look analysis and visualisation. Quantitative analysis of narrow-band spectral features or, more generally, any scientific goals requiring the full spectral resolution of the EPIC cameras, should be based on the standard forward-folding approach implemented in, e.g. `Xspec`[28], `SPEX`[19] or `Sherpa`[20], whereby source flux models are convolved with the instrumental response and the convolution compared to the count spectrum.

More information on the task `efluxer` can be found on the online SAS documentation on individual SAS tasks.

Two examples on how to use `efluxer` are given in section § 4.12.

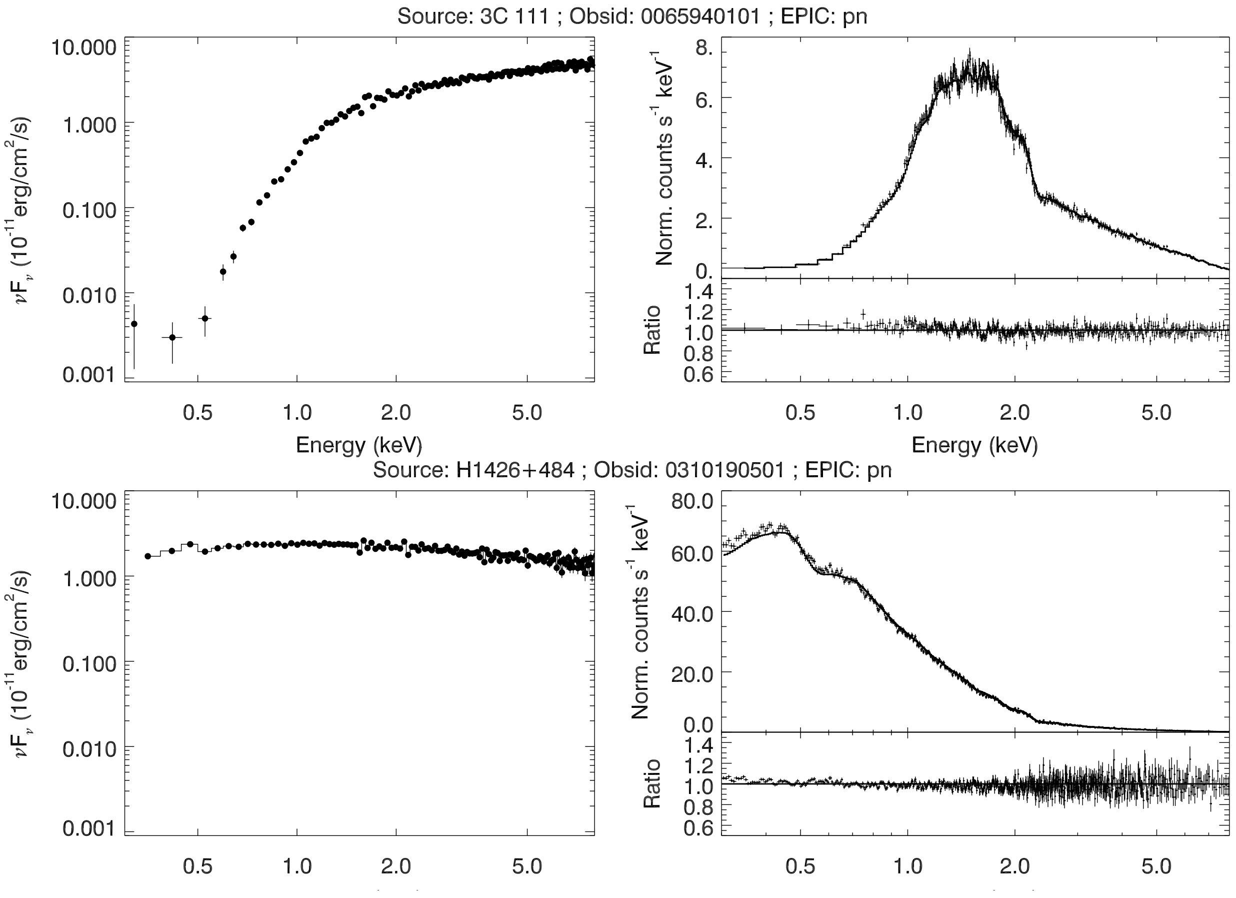


Figure 28: Examples of the results of the `efluxer` task for different spectral shapes. The *left* panels show the fluxed spectra and the *right* panels show the comparison with the actual observed counts once the fluxed spectra have been folded with the effective area and the response matrix (*solid* lines). The *top* panel shows a featureless spectrum heavily obscured so that most of the "soft" events detected are in practice due to redistribution of higher energy photons. The spectrum in the *bottom* panel also corresponds to a featureless source, but with no absorption so that the observed spectrum is strongly peaked at low energies. The same flux scale has been set in the *top* and *bottom* panels to remark the largely different spectral shapes.

4.9 EPIC-pn Out-of-time events

For the EPIC imaging observing modes, photons are not only registered during the actual integration interval but also during the readout of the CCD (shift of charges along a column toward the readout node). These so called Out-of-Time (OoT) events get a wrong RAWY value assigned and thus finally a wrong energy correction (the correction for charge transfer inefficiency (CTI) depends on the distance from the readout node).

The effect of OoT events broadens spectral features and can be seen in EPIC images as a strip of wrongly reconstructed event positions in RAWY. The fraction of OoT events scales with the mode-dependent ratio of integration and readout time and is highest for the pn full frame (6.3 %) and extended full frame (2.3 %) mode (see the XMM-Newton User Handbook [3] for further details).

If OoT events are a problem for the analysis (if highest spectral resolution is required or if a clean image of e.g. extended emission surrounding a bright source is needed), the tasks `epproc` (§ 4.3.2) and `epchain` offer the possibility to simulate OoT events based on the original event list. Note that OoT events do not need to be removed for the purpose of source detection as they are dealt with in the background characterisation stage there (§ 4.12.3 and task description of `esplinemap`). The pipeline tasks need to be run twice, first creating an OoT event list and then the "normal" calibrated event list. The OoT event list is produced by calling the subtask `epevents` with the non-default parameter setting `withoutoftime=yes`. The OoT event list is created treating all events as out-of-time events: after the pattern recognition for the same TIME, PHA, and RAWX a new RAWY value is simulated by randomly shifting the pattern along the RAWY axis and performing the gain and CTI correction afterwards.

`epchain` resembles largely the `epproc` task but can speed up the process to remove OoT events as raw intermediate files from the first run (to create the OoT event list) can be kept for the second run (to create the "normal" calibrated event list) allowing the user to skip some of the already performed processing steps.

An OoT event list from a pn imaging mode ODF can be created to derive output products like images and spectra. The effect of OoT events in images and spectra is highlighted in the next two sections. Details of the necessary procedure to treat OoT events are given in the corresponding pages of the SAS Analysis Threads.

4.9.1 Removing Out-of-Time events from pn images

The effect on images is shown in figure 29 (note the arc-like structures due to single mirror reflections (stray light) at the top left of the FoV).

As mentioned in the previous section, 6.3 % of all events in a full-frame mode event file are OoT events. Because the OoT event list contains the same number of events as the original event list, the OoT image needs to be multiplied by 0.063 before subtracting it from the original image. Assuming that the user has created two images (see § 4.7), one from the OoT and the other from the "normal" event lists (named `image_oot.fits` and `image.fits`, respectively), simple image arithmetics, using for example `FTOOL` tasks, can be used to scale and subtract one image from the other (details in the corresponding pages of the SAS Analysis Threads). This process will remove from the image the strip associated with the OoT events.

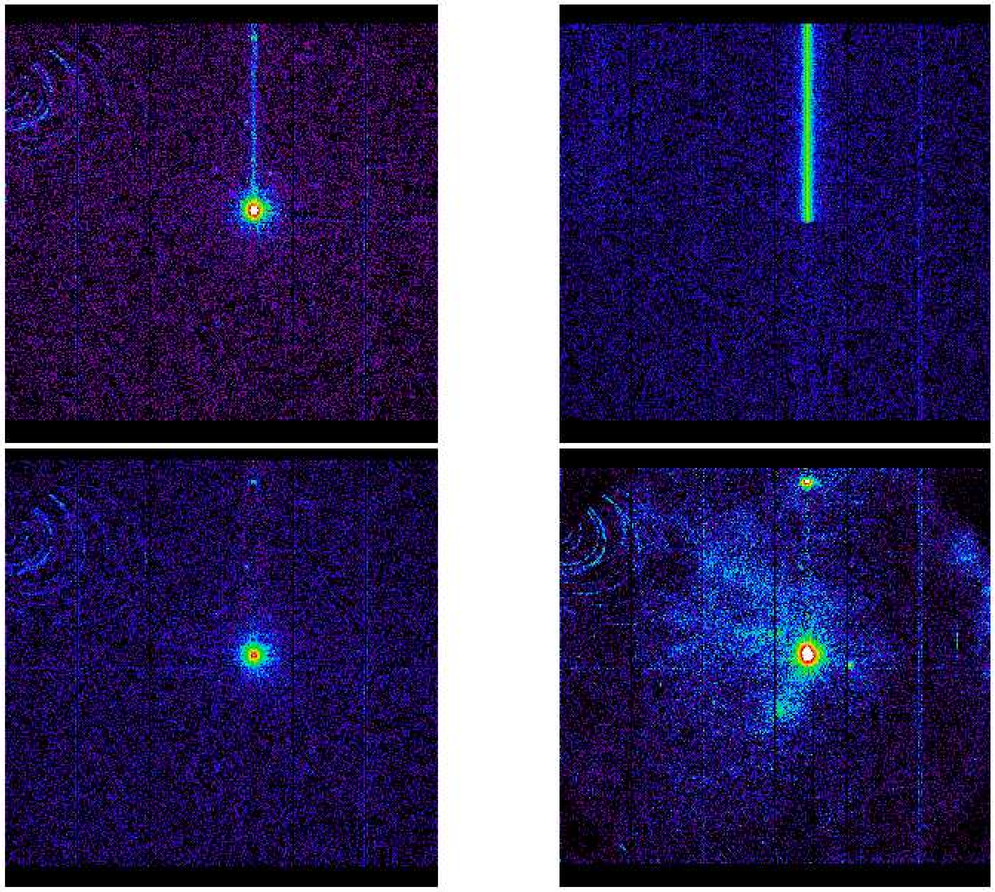


Figure 29: Effect of OoT events on images: The upper left panel contains a 2-10 keV band image of a pn observation of a bright source in full frame mode with the OoT events visible as a strip running along the length of the CCD. The upper right panel depicts the modeled OoT event distribution whereas in the lower left panel these are subtracted from the original image. The lower right panel shows the distribution of cleaned events in the soft (0.2-2 keV) energy band for comparison.

4.9.2 Removing Out-of-Time events from pn spectra

The handling of Out-of-Time events in spectra relies on dealing with FITS tables. As in the case of image cleaning of OoT events (see § 4.9.1), the necessary table manipulation and arithmetics can be performed with `FTOOL` tasks. Again, details of the procedure on how to correct a given spectrum from OoT events are given in the correspondent pages of the SAS Analysis Threads. As an example, the result of correcting for OoT events a given spectrum is shown in figure 30.

The effect of OoT events is reduced to the broadening of the shoulders of a line and can cause a blending of lines. OoT events do not change the Full-width-at-half-maximum. The red spectrum shows that the lines in a spectrum cleared from OoT events are much easier to separate than in an untreated spectrum (black data points). Please keep in mind that the spectrum is displayed in a double logarithmic scale and restricted to a small energy band so as to emphasize the effect. Furthermore, the example shown here is data from the internal calibration source, which is very bright. **For most targets a correction for OoT events in a spectrum should not be**

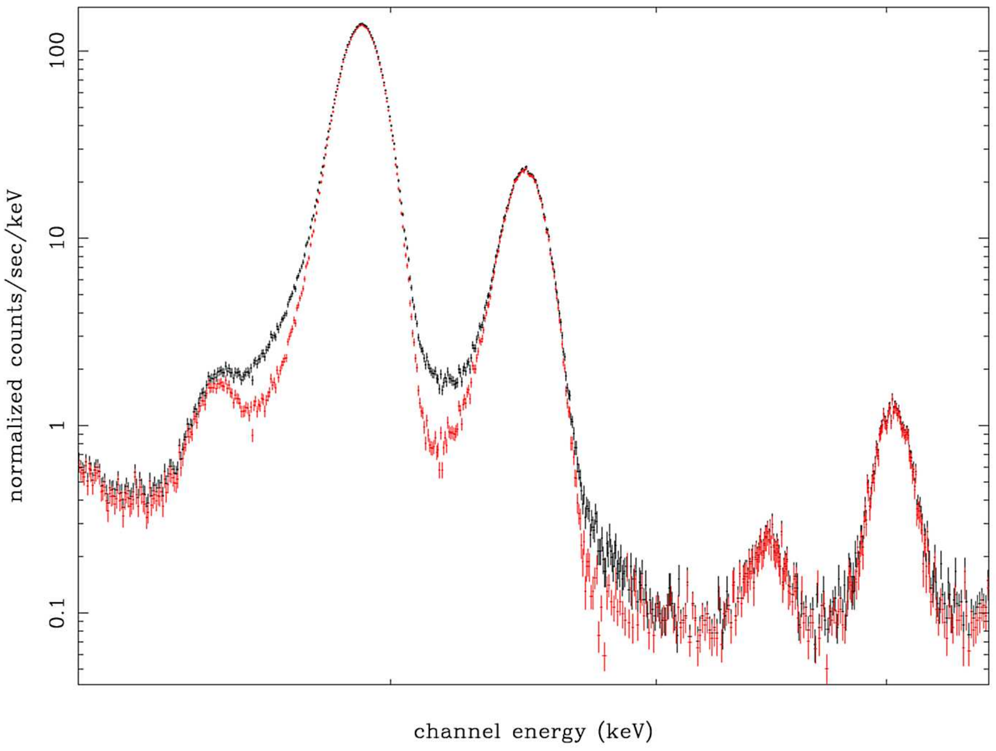


Figure 30: Effect of Out-of-Time events on a source spectrum (in this case the internal calibration source): the black data points display the source spectrum which is still contaminated by OoT events, the red points mark the source spectrum being cleared from OoT events. The energy range displayed is 5-8.5 keV.

necessary. In any case, a correction is only necessary if OoT events overlap with the source under investigation.

4.10 Detecting EPIC X-ray sources

The SAS metatask `edetect_chain` is a powerful tool to perform source detections on EPIC datasets. It allows searching for sources simultaneously in several energy bands, applying different source detection methods, creation of a final combined source list and the computation of sensitivity maps which contain info on point source detection upper limits. It performs the same kind of analysis as occurs in the SOC pipeline to make PPS products.

The several subtasks called from `edetect_chain`, their main purposes, needed input files and created output data sets are summarized in Table 5.

Task	**Purpose**	**Input files**	**Output files**
`eexpmap`	creation of exposure maps	attitude file, event list, image	exposure maps
`emask`	creation of detection masks	exposure map	detection mask
`eboxdetect` (local mode)	sliding box detection	images, exposure maps, detection mask	box detect source list
`esplinemap`	creation of background maps	image, exposure map, detection mask, local box list	background map
`eboxdetect` (map mode)	box detection using background maps	images, exposure maps, detection mask, background maps	map detect source list
`emldetect`	maximum likelihood fitting	images, exposure maps, background maps, map detect list	final source list
`esensmap`	creation of sensitivity maps	exposure map, detection mask, background map	sensitivity map

Table 5: Schematic overview of the EPIC source detection chain and related input and output data sets.

The final output of the EPIC source detection process is a merged source list FITS file which - for every detected source - lists among other parameters the source identification number, the instrument and energy band where it was detected, the source counts, source position and extent, source flux and count rate as well as hardness ratios. The user should read the task description of `emldetect` for a complete list of the output source list columns.

Another output file is a sensitivity map giving (rough) point source detection upper limits (vignetting corrected source count rate corresponding to the likelihood of detection as specified in the parameter file) for each image pixel.

In § 4.12.3 an example of how `edetect_chain` and related subtasks actually perform the EPIC source detection is shown.

The task `ewavelet` provides an alternative source detection method based on a Mexican hat wavelet algorithm which is especially well suited for the detection of extended sources. However, the user is cautioned that the determination of source parameters computed by `ewavelet` is not (yet) in general as reliable as that obtained from `edetect_chain`.

As of SAS v9.0, a set of two new tasks, called `emosaic_prep` and `emosaicproc`, allow the user to perform coherently source detection on several overlapping exposures, or ”pseudo-exposures” as created by the task `emosaic_prep`, from the same or different observations, as well as from any combination of exposures from the three EPIC instruments. The source detection procedure follows the same steps as those described for the task `edetect_chain` for source detection on single exposures. This task has been designed specifically for the treatment of XMM-Newton observations taken in emosaic mode, where a single observation is made up of a number of different pointings.

4.11 Processing EPIC slew data

XMM-Newton conducts EPIC pn science and/or calibration observations during some slews from one target to another. The following sections describe how to analyse these data using the SAS task `eslewchain`.

4.11.1 The slew data

An EPIC slew is packaged into a single raw data file called a Slew Data File (SDF). This is the equivalent of a pointed observation ODF (§ 2.1). It contains the recorded events, for the three EPIC detectors, and accompanying housekeeping and attitude information for the slew.

The SDF for a particular slew observation can be downloaded from the XMM-Newton Science Archive. When searching for slews in the archive care should be taken to set the *Observations Status* to *Any*.

Slews are made using the observing mode of the previous observation. For the pn camera the useful slewing modes are PRIMEFULLWINDOW, EXTENDEDFULLWINDOW and LARGEWINDOW. Other modes contain too little data to be worth processing.

4.11.2 Processing Steps

The steps to be followed to process a slew datafile are detailed below:

- Download the slew datafile (SDF) into a clean directory, unpack it and point to the directory with the environment variable `SAS_ODF`
- Run `cifbuild` and point to the CCF with `SAS_CCF` (see § 2.3.3)
- Run `odfingest` (once finished, set the environment variable `SAS_ODF` to the new *SUM.SAS file just created) (see § 2.3.4)
- Run `epproc` (see § 4.3.2)
- Set the SAS_ATTITUDE environment variable to RAF

```
export SAS_ATTITUDE=RAF [sh, bash, ksh]

setenv SAS_ATTITUDE RAF [csh, tcsh]
```

Remember to unset this variable if further processing of pointed observations is going to be performed.

- Run `eslewchain`

The first four steps are identical to the processing of pointed data.

The task `eslewchain` divides the slew into a series of small images which are roughly 1 degree by 0.5 degrees in size. Images are created in several energy bands:

1 = 0.2–0.5 keV
2 = 0.5–1.0 keV
3 = 1.0–2.0 keV
7 = 2.0–12.0 keV
6 = 0.2-2.0 keV
8 = 0.2-12.0 keV

For pn slews, images are created using a selection expression of the form:

```
FLAG==0 && PATTERN==0
```

for energies between 200-500 eV and

```
FLAG==0 && PATTERN<=4
```

for energies > 500 eV

NB: *It is imperative to use the Raw Attitude File (RAF) during the processing. If the default attitude is used then source positions will be wrong by roughly 1 arcminute.*

4.11.3 Output files

EPIC images are produced with name P*obsid*PNS003IMAGE_*bnnn*.ds, where *nnn* is the subimage number and *b* is the energy band. The intermediate event files used to create each image, of name P*obsid*PNS003PIEVLI*nnn*.ds are not removed from the disk. These could be used to extract a spectrum of a source although specific software to perform this task does not yet exist. EPIC exposure maps are produced with the names P*obsid*PNS003EXPMAP*bnnn*.ds for bands 6, 7 and 8 only. Finally, a set of files with names P*obsid*PNS003UNFDAT8*nnn*.ds are produced which can be used for diagnostics. These files contain images with no filtering, pattern or energy cut applied.

4.11.4 Source Detection

The set of output files created by `eslewchain` may be used to search for sources using the task `eslewsearch`.

4.11.5 Background

By default the slew processing does not include any filtering for periods of high background. Such a filtering would lead to blank regions in the slew images. It is has been seen that strong background flares lead to a section of the slew being relatively bright. At first sight, this is indistinguishable from a slew image of a large Supernova remnant (SNR). Usually photon energies can be used to make the distinction. High background usually leads to an excess at high energies (>2 keV) whereas SNR are usually brightest at energies below 2 keV.

In high background regions, source search algorithms will tend to find a large number of spurious sources.

4.12 Processing examples of EPIC data

4.12.1 Example of calibrated events files creation

After a proper installation of the SAS software package, EPIC calibrated events lists maybe created and quickly inspected by means of the following recipe:

- create and move to a working directory
- point to an observation data file (ODF)

  ```
  setenv SAS_ODF /path/to/<ODF>
  ```

- generate a calibration index file (CIF) from a repository of current calibration files (CCFs).

  ```
  cifbuild
  ```

- point to the newly created `ccf.cif` calibration index file

  ```
  setenv SAS_CCF /path/to/<ODF>/ccf.cif
  ```

- extend the ODF summary file with data extracted from the instrument housekeeping data files and the calibration database creating a new summary file

  ```
  odfingest outdir=$SAS_ODF odfdir=$SAS_ODF
  ```

- run e.g the EPIC MOS or/and pn pipeline processing

  ```
  emproc &
  epproc &
  ```

  or, alternatively, use the chain tasks

  ```
  emchain &
  epchain &
  ```

  After some time, a set of calibrated event files will have been created in the working directory including the merged event lists of all active MOS and pn CCDs, respectively.

- In order to inspect the content of these files, the Graphical User Interface (GUI) of the `xmmselect` task can be started:

  ```
  xmmselect -d &
  ```

- to select one of these newly created MOS or pn event files as input data set, either enter its name directly in the `table` parameter window or click the button on the right hand side to start the file browser: in the right panel of the dataset browser you can select one of the event lists by double-clicking on it with the left mouse button, then search for the table extension called EVENTS, click on the left mouse button again to select it and finally click on "Ok" at the bottom right of the dataset browser panel.

- press ”Run” in the `xmmselect` window. The main `xmmselect` window (figure 20) appears.
- make use of the ”Product selection” tasks offered via `xmmselect` to generate filtered event lists, images, spectra or rate curves.

4.12.2 Example of EPIC product generation: images, spectra & light curves

The following example illustrates a simple analysis session which aims to extract an image, spectrum and light curve of a point source within the field of view of a single EPIC camera taken in imaging mode.

It is assumed that a calibrated EPIC event list (either from the pipeline processing or from running the EPIC chain tasks) is present in the working directory and that the setup steps (`cifbuild`, `odfingest` and the definition of the SAS environment variables, see § 4.12.1) have already been performed.

The following analysis steps are described:

1. Create light curves to check for times of background flares.
2. Filter the EPIC event list to exclude bad events and periods of high background.
3. Create images of the EPIC data.
4. Extract source and background spectra for a bright point-like field source.
5. Create RMF and ARF files for this source.
6. Alternatively, make use of the `especget` meta-task to perform spectral analysis steps 4 and 5 in one go.
7. Prepare the spectra for further analysis with `Xspec`.
8. Create a light curve for the source.

Commands to analyse the spectrum using `Xspec` and the light curve using `Xronos` are beyond the scope of this document. Please, check the manuals of these programme packages and the SOC provided SAS data analysis threads (available from the SAS web page) for further info.

4.12.2.1 Working from the command line

The user can perform the described analysis with command lines by executing the following steps:

In order to avoid long names and path, it might be convenient to first define the name of the input calibrated event list as a variable:

```
set evfile=/path to PPS directory/P0123700401PNS003PIEVLI0000.FIT
```

where as an example the pn event list from the pipeline processing of the public Lockman Hole data set is shown.

1. Create a light-curve for the observation to check for flaring high background periods (which are best visible above 10 keV):

```
evselect table=$evfile withrateset=yes rateset=rates.fits \
         timecolumn=TIME timebinsize=100 \
         makeratecolumn=yes maketimecolumn=yes \
         expression='#XMMEA_EP && PI in [10000:12000] && (PATTERN==0)'
```

   Note, in case of MOS `#XMMEA_EM && PI > 10000 && (PATTERN==0)` shall be used.

   Plot the light-curve (see figure 31):

```
dsplot table=rates.fits x=TIME y=RATE &
```

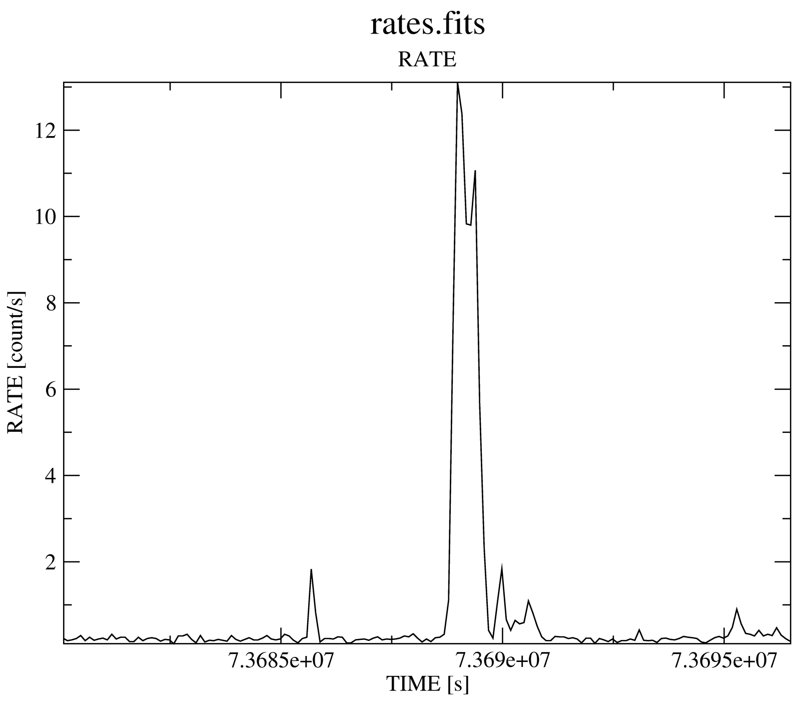


Figure 31: Light-curve of the example data set. Flaring high background periods are clearly visible.

   Determine a threshold on the light-curve, defining *low background* intervals (in our example: 0.4 counts/s) and create a corresponding good time interval (GTI) file:

```
tabgtigen table=rates.fits expression='RATE<=0.4' gtiset=gti.fits
```

   Note: the recommended cut value for MOS observations is 0.35 counts/s but the choice of the thresholds strongly depends on the science the user is interested in.

2. Create an event list which is free of high background periods. Also this might be the place to restrict the further analysis to the well calibrated patterns and energy band:

```
evselect table=$evfile withfilteredset=true \
         filteredset=filtered.fits \
         keepfilteroutput=true destruct=true \
         expression='(gti(gti.fits,TIME) && (PI in [100:15000]) \
              && (PATTERN<=4))'
```

   Note, in case of MOS (`PATTERN<=12`) shall be used. Create a new light curve to make sure that the flaring background time intervals were removed:

```
evselect table=filtered.fits withrateset=yes rateset=rates_new.fits \
         timecolumn=TIME timebinsize=100 maketimecolumn=yes \
         makeratecolumn=yes expression='#XMMEA_EP \
         && PI in [10000:12000] && (PATTERN==0)'
```

   Note, in case of MOS `#XMMEA_EM && PI > 10000 && (PATTERN==0)` shall be used.

   Plot the new light-curve (see figure 32):

```
dsplot table=rates_new.fits x=TIME y=RATE &
```

   From now on, the filtered events file (`filtered.fits`) will be used for further analysis. In the case of the example data set, the number of events in the filtered event list is less the half of what the original event list had, a fact which will speed up further processing significantly. The size of the event list (especially in case of bright sources) can be further reduced a lot by also excluding the following columns: RAWX/Y, DETX/Y, PHA.

3. Create a sky image of the filtered data set:

```
evselect table=filtered.fits withimageset=true imageset=image.fits \
         xcolumn=X ycolumn=Y \
         imagebinning=binSize ximagebinsize=80 yimagebinsize=80
```

   and display the image with `ds9`:

```
ds9 image.fits &
```

   The parameter settings `imagebinning=binSize` and `x/yimagebinsize=80` bin the image into squared pixels of $80 \times 0.05 = 4$ arcsec (0.05 arcsec being the unit of the X, Y sky coordinate system).

   Specifying an additional selection expression of the form `expression='PI in [..:..]'` allows creation of images in different energy bands, e.g., figure 33 shows the image in the energy range 0.5-7 keV.

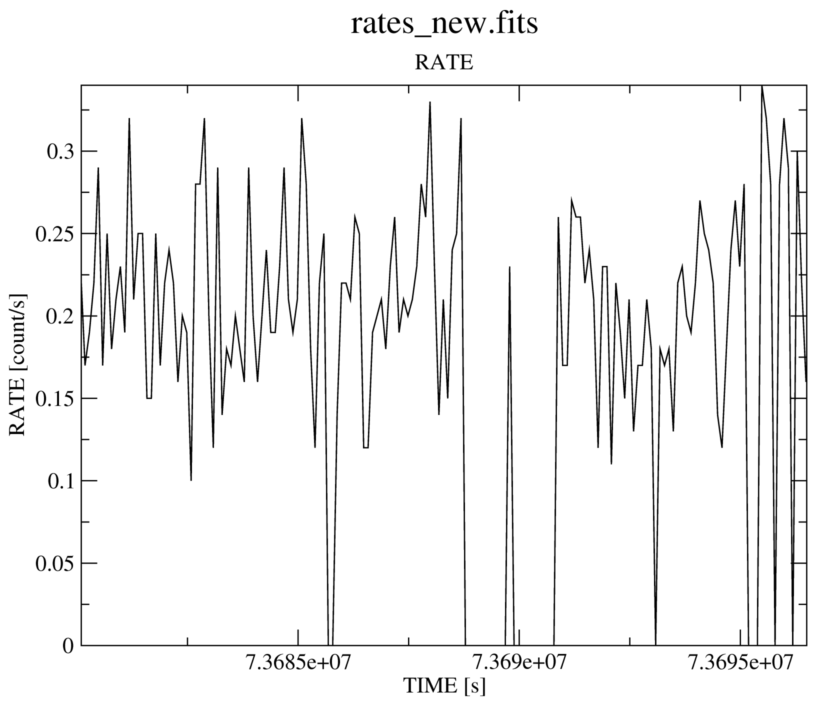


Figure 32: Light-curve of the example data set after removal of flaring high background periods.

4. Extract source and background spectra for a bright point-like field source: in the displayed image a region around the source can be selected by positioning the cursor on the source center. Keeping the left mouse button pressed, the size of the circular extraction region can be changed. Clicking after-wards again on the region selects it. With the left mouse button the position and size of the region can interactively be changed. It is also possible to change characteristic region parameters via double clicking on the region as well as to save a region via the "Region/Save Regions..." menu in `ds9`.

   To apply the specified region as a spatial filter expression in `evselect`, the properties of the region need to be given in physical sky coordinates. To do this, make sure that the coordinates and radius are displayed in physical units in the selection region properties window.

   In our example, the spatial selection expression for the source spectrum is `(X,Y) IN circle(26285.6,22842.1,600)`. The extraction radius is 30 arcsec. The same values would also be propagated into the selection expression by pressing the "2D Region" button in `xmmselect`.

   The source spectrum is extracted with the following command line:

```
evselect table=filtered.fits withspectrumset=yes \
        spectrumset=spectrum.fits energycolumn=PI \
        withspecranges=yes specchannelmin=0 specchannelmax=20479 \
```

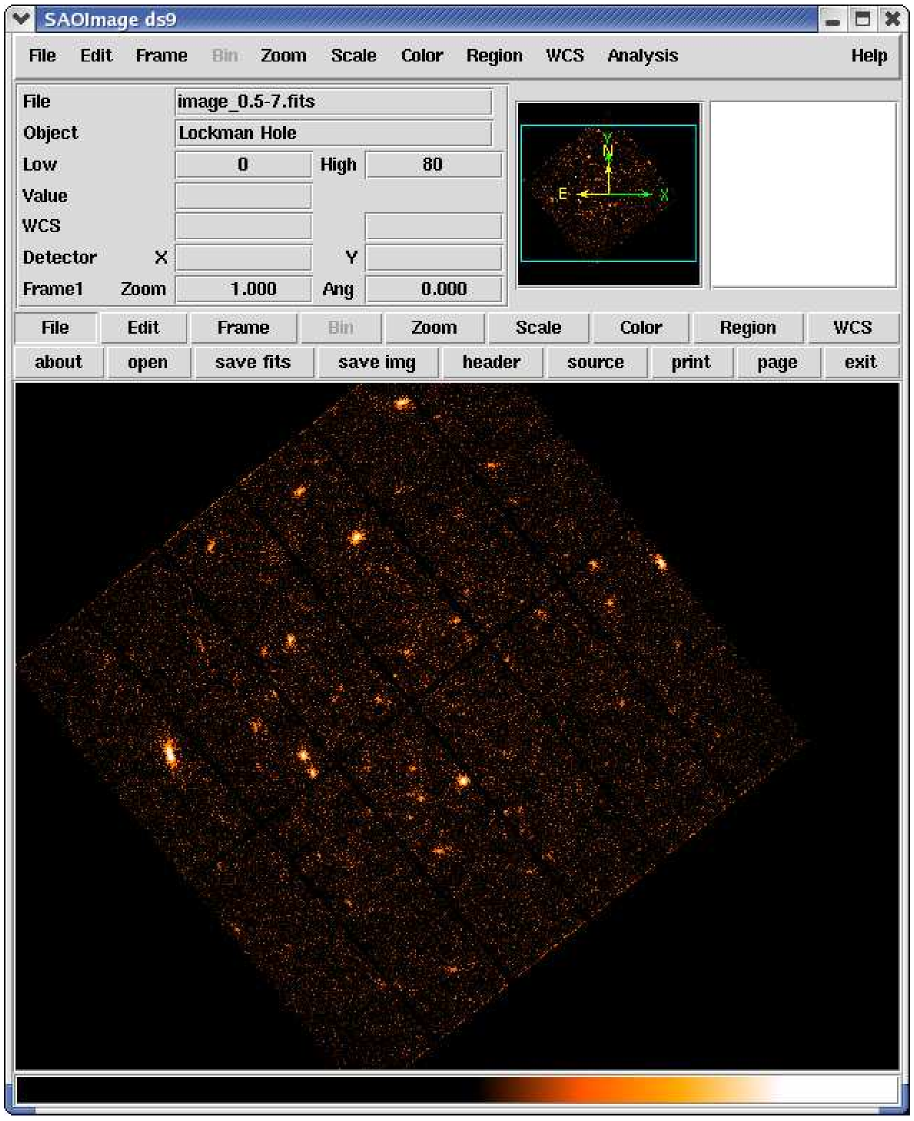

SAOImage ds9
File Edit Frame Bin Zoom Scale Color Region WCS Analysis Help
File image_0.5-7.fits
Object Lockman Hole
Low 0 High 80
Value
WCS
Detector X Y
Frame1 Zoom 1.000 Ang 0.000
File Edit Frame Bin Zoom Scale Color Region WCS
about open save fits save img header source print page exit

Figure 33: Sky image of the example data set in the energy range 0.5-7 keV displayed with `ds9`.

```
    spectralbinsize=5 \
    expression='((X,Y) IN circle(26285.6,22842.1,600)) && \
                (FLAG==0) && (PATTERN<=4)'
```

Parameters `specchannelmax=20479` and `spectralbinsize=5` are the recommended settings for a pn data set. In the case of MOS data, they should be set to `specchannelmax=11999` and `spectralbinsize=5`. This setup allows the optional usage of the "canned" response matrices.

Including `(FLAG==0)` in the selection expression is recommended for pn. This selection is even more restrictive than the `#XMMEA_EP` event attribute flag as it rejects, in addition, events which are close to CCD gaps or bad pixels. In the case of MOS, the filter expression `#XMMEA_EM` might be sufficient.

For pn the spectral analysis is restricted to the better calibrated single and double events ((PATTERN<=4)). In the case of MOS, all valid patterns ((PATTERN<=12)) might be included.

The source spectrum can be displayed with the following command:

```
dsplot table=spectrum.fits &
```

In a next step, one needs to extract a background spectrum:

In our pn example the source is located close to the edge of a CCD at a RAWY position of about 138. A surrounding annulus for the background extraction would include the CCD gap and eventually also part of a neighboring CCD. Hence in this case it might be better to define the background via a circle on the same CCD where the source is located at roughly the same distance from the readout node (same RAWY as the source) placed in a source free region (see figure 34 for the selected source and background regions parameters):

```
evselect table=filtered.fits withspectrumset=yes \
         spectrumset=background.fits energycolumn=PI \
         withspecranges=yes specchannelmin=0 specchannelmax=20479 \
         spectralbinsize=5 \
         expression='((X,Y) IN circle(25120.3,21879.9,600)) && \
                     (FLAG==0) && (PATTERN<=4)'
```

The background spectrum can be displayed again with the following command:

```
dsplot table=background.fits &
```

In the next step, the area of the extraction regions used to make the source and background spectral files must be calculated taking into account CCD boundaries and bad pixels. The area is written into the header of the SPECTRUM table of the input file as the keyword BACKSCAL:

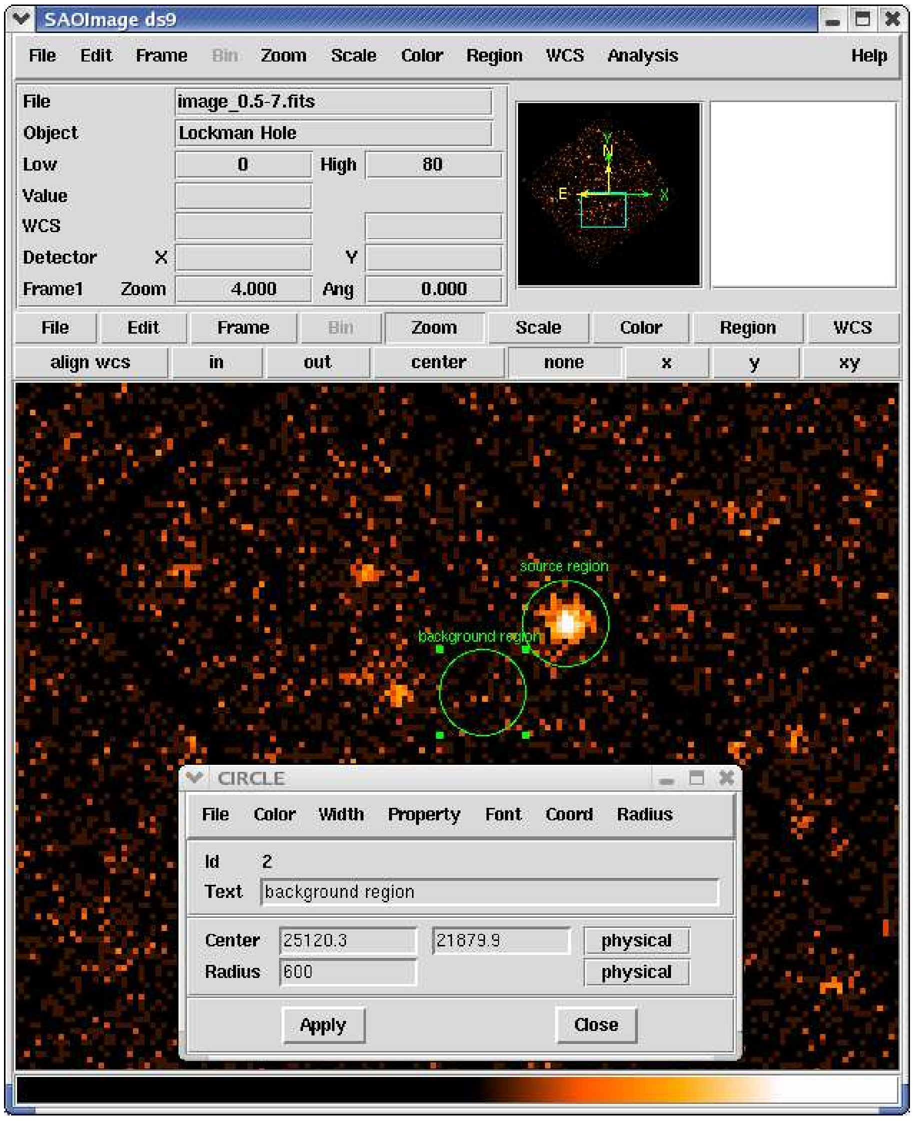
```
backscale spectrumset=spectrum.fits badpixlocation=filtered.fits

backscale spectrumset=background.fits badpixlocation=filtered.fits
```

Note, if spectra are created via the xmmselect task, backscale will have automatically been applied ”on the fly” during the product generation process.

5. Create response matrix files (Redistribution Matrix File (RMF) and Ancillary Response File (ARF)) using the rmfgen and arfgen tasks:

```
rmfgen spectrumset=spectrum.fits rmfset=spectrum.rmf
```

An alternative approach to obtain a RMF file is to use the ready-made ”canned” response matrices available from the rmf files at the EPIC Response Files page (http://www.cosmos.esa.int/web/xmm-newton/epic-response-files)


SAOImage ds9
File Edit Frame Bin Zoom Scale Color Region WCS Analysis Help
File
Object
Low
High
Value
WCS
Detector X Y
Frame1 Zoom
Ang
File Edit Frame Bin Zoom Scale Color Region WCS
align wcs in out center none x y xy
source region
background region
CIRCLE
File Color Width Property Font Coord Radius
Apply Close

File: image_0.5-7.fits
Object: Lockman Hole
Low: 0 High: 80
Frame1 Zoom: 4.000 Ang: 0.000

Id 2
Text background region
Center 25120.3 21879.9 physical
Radius 600 physical

Figure 34: Selection regions for the extraction of source and background spectra.

```
arfgen spectrumset=spectrum.fits arfset=spectrum.arf \
       withrmfset=yes rmfset=spectrum.rmf \
       badpixlocation=filtered.fits
```

Note, `arfgen` reads the pattern range from the data subspace (DSS) information in the spectrum dataset, and accumulates the quantum efficiency curves over those patterns, which are then combined to the other constituents of the ARF. Be aware that the entire range of allowed patterns (0-12 for the pn and 0-31 for the MOS, respectively) are assumed if no pattern range was found in the DSS.

6. Alternatively, make use of the `especget` meta-task to perform spectral analysis steps 4 and 5 in one go

Assuming that the user wants to use the same extraction regions for the source and background spectra as given above, the generation of spectra and related response files can be performed in one go with the following command:

```
especget table=filtered.fits filestem=mysource \
         srcexp='(X,Y) IN circle(26285.6,22842.1,600)' \
         backexp='(X,Y) IN circle(25120.3,21879.9,600)'
```

By default the following event selection is added to the spatial selection expressions: for pn `(FLAG==0)&&(PATTERN<=4)` and for MOS `#XMMEA_EM&&(PATTERN<=12)`. The spectra are generated with spectral ranges and binnings automatically set in a way that canned response matrices (§ 4.8.2) could be used. The computation of the area of the extraction regions is performed "on the fly". In addition, `especget` writes the names of the created files into the source spectrum header keywords BACKFILE, RESPFILE, ANCRFILE. These may be automatically read by spectral fitting programmes to link the files and perform area weighted background subtraction.

The parameter `filestem` defines the names of the produced output files. In the example given above, `especget` generates the following output files:

- mysource_src.ds: the source spectrum
- mysource_bgd.ds: the background spectrum
- mysource_src.arf: the source related Ancillary Response File (ARF)
- mysource_src.rmf: the source related Redistribution Matrix File (RMF)

Note, if `xmmselect` is used to generate "OGIP Spectral Products" (see § 4.8.1), the user can interactively define source and background regions and (before `especget` is started) a source region optimization is performed via the task `eregionanalyse` (see 4.7.6).

7. Prepare the spectra for further analysis with `Xspec`

   The task `specgroup` can be used to rebin the the spectrum. In the following example the spectrum is rebinned in order to have at least 25 counts for each background-subtracted spectral channel and not to oversample the intrinsic energy resolution by a factor larger then 3:

```
specgroup spectrumset=spectrum.fits mincounts=25 oversample=3 \
    rmfset=spectrum.rmf arfset=spectrum.arf \
    backgndset=background.fits
```

   If the source spectrum was **not** generated with `especget`, the `specgroup` also offers the possibility to fill the keywords `RESPFILE`, `ANCRFILE`, and `BACKFILE` in the header of the spectral file. This is mandatory if users want to load the spectral file into XSPEC versions later then 12 for further analysis (as in the example given above).

8. Create a light-curve for the source:

```
evselect table=filtered.fits withrateset=yes \
         rateset=lightcurve.fits timecolumn=TIME timebinsize=1 \
         expression='((X,Y) IN circle(26285.6,22842.1,600))'
```

The `Xronos` programme package can now be used to produce a binned light-curve, to calculate a power spectrum, search for periodicities etc.

The data analysis based on command lines was described here, as well as combining command lines into a script which might offer a good method for further re-performing of (part of) a data analysis session (see § 3.1 for a discussion of possible advantages of a GUI based analysis).

4.12.2.2 Inspection of spectra or timeseries using the command line

Although `xmmselect` interacts in a convenient way with the external plotting programme `grace`, the user might want to plot, inspect or export spectra and timeseries which have been created in an already closed `xmmselect` session or via `evselect` from the command line. As the produced output files are FITS files, the `FTOOLS` task `fv` and `fplot` offer many possibilities here, but also the SAS task `dsplot` can be used. Assuming that the spectrum or time series is named *product.fits*:

- A plot can be generated:

  ```
  dsplot table=product.fits
  ```

- Postscript files can be created.

  ```
  dsplot table=product.fits plotter='gracebat -printfile product.ps'
  ```

- Spectrum and timeseries files can also be dumped into an ASCII file using the command `dstoplot`.

  ```
  dstoplot table=product.fits > product.asc
  ```

4.12.2.3 Generation of spectra using `efluxer`

- A fluxed spectrum with default binning

  ```
  efluxer spectrumset=my_src.ds arfset=my_src.arf \
     respset=my_src.rmf fluxedset=my_src_fluxed.ds
  ```

  The file `my_srcbgd_fluxed.ds` contains the source spectrum in flux units after.

- A background-subtracted fluxed spectrum with default binning

  ```
  efluxer spectrumset=my_src.ds arfset=my_src.arf respset=my_src.rmf \
     backgndset=my_bgd.ds fluxedset=my_srcbgd_fluxed.ds
  ```

  The file `my_srcbgd_fluxed.ds` contains the source spectrum in flux units after background subtraction.

Users are warmly encouraged to take into account the caveats on the usage of this task outlined in § 4.8.7.

4.12.2.4 Extraction of a X-ray corrected light curve for a point-like source

As an example case, the extraction of a light curve from a pn event list (`PN.evt`) will be considered. A similar recipe applies for a MOS event list.

1. Set up your SAS environment (see § 2.3.1)
2. Extract an image (in sky coordinates in this example; extraction in detector - DET[XY] - coordinates is possible as well)

   ```
   evselect table=PN.evt:EVENTS imagebinning=binSize \
     imageset=PNimage.fits withimageset=yes \
     xcolumn=X ycolumn=Y ximagebinsize=80 yimagebinsize=80
   ```

3. Display the image

   ```
   imgdisplay withimagefile=true imagefile=PNimage.fits
   ```

4. Select the region, from which the light curve shall be accumulated, using the Region/Circle in `ds9` (see figure 35).
5. Double-click with the cursor on the defined region. A window pops up, showing the properties of the region (figure 36). Write down the coordinates of the Center (25910.5, 25870.5) and the Radius (400).

   Units of sky coordinates (X,Y) are 0.05 arcsec, hence the radius in our example is 20 arcsec.
6. **Be aware**: if you are interested in very short time periods, such as they appear in pulsars of cataclysmic variables, you have to perform a barycentric correction. This means that the arrival time of a photon is shifted as is it would have been detected at the barycenter of the solar system (the center of mass) instead at the position of the satellite. In this way, the data are comparable. The SAS task `barycen` performs this correction. It is advisable first to copy the event list since the `TIME` column of the event list is directly overwritten by the barycentric corrected times

   ```
   cp PN.evt PN_evlist.fit

   barycen table=PN_evlist.fit
   ```

7. Now you can extract a source+background light curve, using all the selection expressions defined so far. In the example, the binsize is 100 seconds. Please take into account that operating with non-synchronous time series can introduce artifacts when they are added or subtracted by programmes such as the ftools `lcmath`. From SAS v8.0 onwards, there is no need to do so, since by default the start time is set to the beginning of the exposure. You can override this by using the parameter `timemin` and `timemax`.

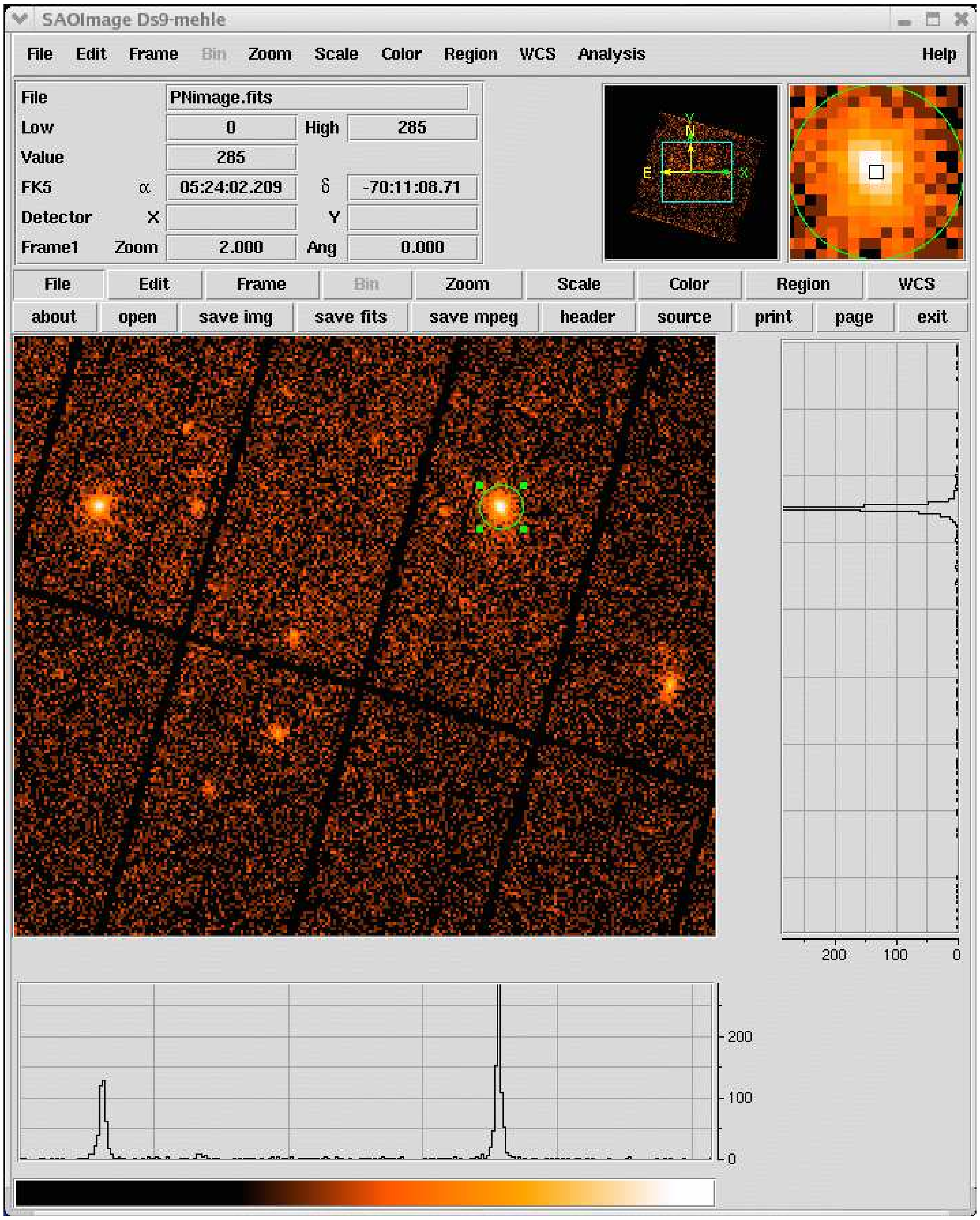
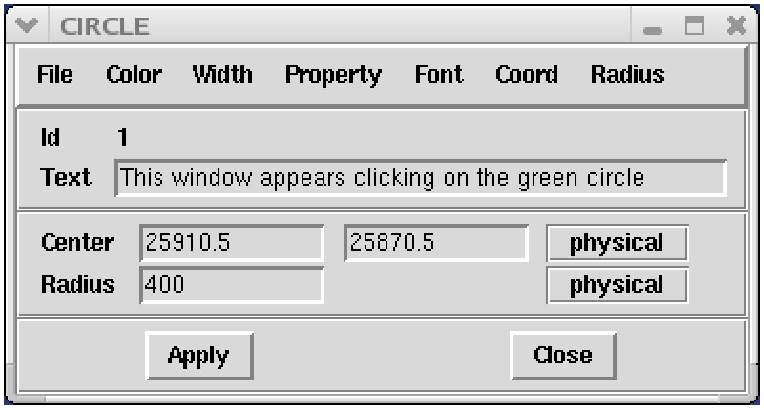

SAOImage Ds9-mehle
File Edit Frame Bin Zoom Scale Color Region WCS Analysis Help
File PNimage.fits
Low 0 High 285
Value 285
FK5 α 05:24:02.209 δ -70:11:08.71
Detector X Y
Frame1 Zoom 2.000 Ang 0.000
File Edit Frame Bin Zoom Scale Color Region WCS
about open save img save fits save mpeg header source print page exit
200 100 0
200 100 0

Figure 35: ds9 main window. A circular region (green circle) has been defined using the highlighted menu.

```
evselect table=PN.evt energycolumn=PI \
  expression='#XMMEA_EP&&(PATTERN<=4)&& \
  ((X,Y) IN circle(25910.5,25870.5,400))&&(PI in [200:10000])' \
  withrateset=yes rateset="light_curve.fits" timebinsize=100 \
```



Id 1
Text This window appears clicking on the green circle
Center 25910.5 25870.5 physical
Radius 400 physical

Figure 36: Selection region properties window, pop'd-up by double-clicking on the region in the main `ds9` window.

```
        maketimecolumn=yes makeratecolumn=yes timemin=126991800 \
        timemax=130000000
```

The parameter `makeratecolumn=yes` produces a light curve in count rates (with errors). Otherwise the light curve is produced in counts (with errors).

8. Repeat step 4. to 6. above to determine the region, from which the background light curve is to be extracted. It will be assumed in what follows that the extraction region correspond to an annulus, centered in (25910.5,25870.5) and with inner and outer radii 1000 and 2000 pixels, respectively.

9. Extract a background light curve, using all the selection expressions defined so far, and the same binsize (100 seconds) and energy range as for the source+background light curve

```
evselect table=PN.evt energycolumn=PI \
  expression='#XMMEA_EP&&(PATTERN<=4)&& \
  ((X,Y) IN annulus(25910.5,25870.5,1000,2000)) \
  && (PI in [200:10000])' \
  withrateset=yes rateset="light_curve_background.fits" \
  timebinsize=100 \
  maketimecolumn=yes makeratecolumn=yes \
  timemin=126991800 timemax=130000000
```

The light curves are OGIP-complaint, and therefore analyzable with standard XRONOS-like (`Xronos`) LHEASOFT packages.

10. However, light curves obtained in such a way should be corrected to account for a number of effects which can have an impact in the detection efficiency, like vignetting, bad pixels, PSF variation and quantum efficiency, as well as to account for time dependent corrections within a exposure, like dead time and GTIs. Since all these corrections can differ between source and background light curves, the background subtraction has to be done accordingly. The SAS task `epiclccorr` performs all of these corrections at once. It requires as input both light curves (which are used to

establish the binning of the final corrected background subtracted light curve) and the event file. A simple command line call:

```
epiclccorr srctslist=PN_lightcurve_raw.FIT \
           eventlist=PN_evlist.FIT \
           outset=PN_lccorr.fit \
           bkgtslist=PN1_lc_bck.FIT \
           withbkgset=yes \
           applyabsolutecorrections=yes
```

11. Plot the resulting light curves, eg.

```
dsplot table=PN_lccorr.fit withx=yes x=TIME withy=yes y=RATE
```

This command will launch the window shown in figure 37.

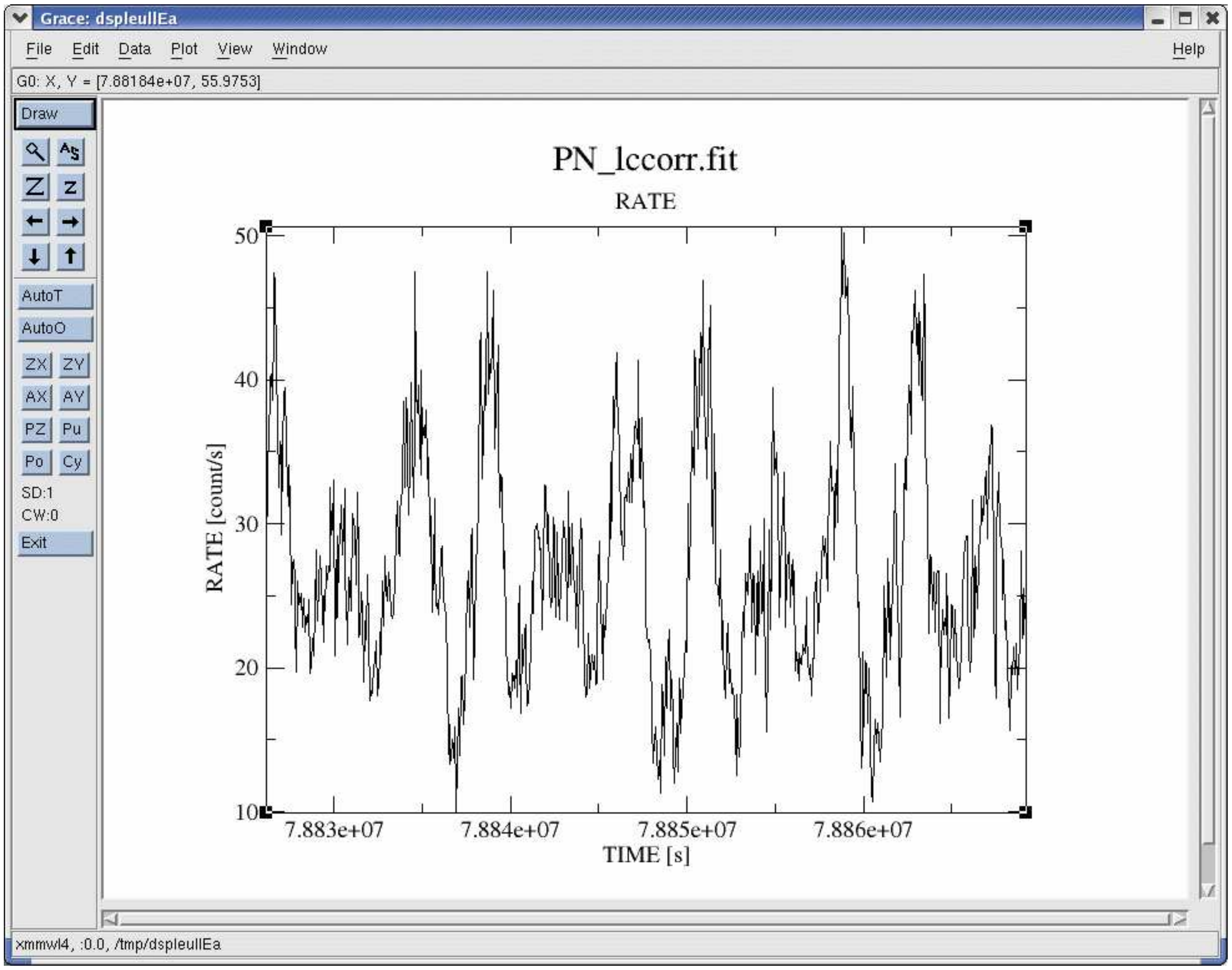


Figure 37: `xmgrace` window, containing the background subtracted exposure corrected light curve.

4.12.3 Source detection example

In the following section (§ 4.12.3.1) an example on how to perform EPIC source detection analysis calling in sequence the individual `edetect_chain` subtasks is shown. This gives detailed information about the detection process. If, however, the user is happy with the default parameter settings for a standard source detection session, he/she might skip this section and continue directly with § 4.12.3.2 where the source detection is performed in one go via the `edetect_chain` task.

In the following it is assumed that the user has created a calibrated EPIC event list (or uses one from the pipeline processing) and has cleaned it for high flaring background periods (see § 4.4.4 and analysis step 1 and 2 in § 4.12.2.1). The assumed name of this filtered event list is `filtered.fits`.

The user can make use of the pipeline produced images (IMAGE_1 to IMAGE_5, see Table 4). Alternatively, images in these or different energy bands need to be generated first with e.g. the following command (see also § 4.12.2.1, analysis step 3):

```
evselect table=filtered.fits withimageset=true imageset=image_b1.fits \
         xcolumn=X ycolumn=Y imagebinning=binSize ...\
```

in case of MOS, a binsize of 22 = 1.1 arcsec fits well the camera pixel size, all valid patterns should be included, and the MOS specific bit mask should be used:

```
         ... ximagebinsize=22 yimagebinsize=22 \
         expression='(PI in [200:500])&&(FLAG==0)&&(PATTERN in [0:12])&&#XMMEA_EM'
```

in case of the pn, a binsize of 82 = 4.1 arcsec fits well the camera pixel size, all single and double events should be included, and the PN specific bit mask should be used:

```
         ... ximagebinsize=82 yimagebinsize=82 \
         expression='(PI in [200:500])&&(FLAG==0)&&(PATTERN in [0:4])&&#XMMEA_EP'
```

To perform source detection in all the standard pipeline processing energy bands, four more images need to be generated, modifying the energy selection expression in the following way: for `image_b2.fits` use (PI in [500:2000]), for `image_b3.fits` use (PI in [2000:4500]), for `image_b4.fits` use (PI in [4500:7500]) and for `image_b5.fits` use (PI in [7500:12000]). The energy bands are defined via PI intervals in units of eV. Note that such a multi-band approach to source detection is not essential (source detection can also be performed on a single energy band).

With images extracted in the required energy bands, the user now can start the EPIC source detection process, either performing it step by step (§ 4.12.3.1) or in one go via the `edetect_chain` meta task (§ 4.12.3.2).

4.12.3.1 EPIC source detection performed via single task commands

The user can further make use of the pipeline produced exposure maps (EXPMAP1 to EXPMAP5, see Table 4). Alternatively, exposure maps in different energy bands need to be generated with the `eexpmap` task. This task makes use of calibration information on the spatial quantum efficiency, filter transmission, mirror vignetting and field of view to calculate for each attitude bin the exposure time values projected onto the sky. Assuming that the attitude information is available from the file `attitude.fits` (created by the `atthkgen` task; alternatively, the attitude file exists as a pipeline product with file identification ATTTSR), exposure maps `image_biexp.fits` (i = 1 to 5) are generated in the following way:

```
eexpmap attitudeset=attitude.fits eventset=filtered.fits imageset=image.fits \
        expimageset='image_b1exp.fits image_b2exp.fits image_b3exp.fits \
                     image_b4exp.fits image_b5exp.fits' \
        pimin='200 500 2000 4500 7500' pimax='500 2000 4500 7500 12000'
```

The imageset `image.fits` can be any of the already created energy band images. It is only used to extract information from the FITS header about the Instrument ID, Mode/Submode, filter ID, GTI and WCS keywords.

In the next step, a detection mask needs to be generated. The detection mask is a FITS image containing the integer values 0 and 1 where 1 marks the image area on which subsequent source searching will be performed. The following command should be performed:

```
emask expimageset=image_biexp.fits detmaskset=mask.fits
```

The expimageset `image_biexp.fits` can be any of the previously created exposure maps. The user should inspect the created mask with `ds9` to see if the area selection is appropriate for further source detections. If not, the values of the threshold parameters `threshold1` and `threshold2` can be tuned. By default, the detection mask contains 0 where the value of the exposure map is less than 30% of the maximum exposure (`threshold1`) and where the gradient of the exposure map is steeper than 0.5 (`threshold2`).

Now all necessary files have been generated to start the sliding box source detection in the so-called local mode. The purpose of the local detection step is to provide an input list of source positions for task `esplinemap` (see below) which then constructs a background map from the non-source locations. Source counts are accumulated from a 3×3 or 5×5 (controlled by parameter `boxsize`, default value = 5, also used in the SOC pipeline) pixel window and the background is determined from the surrounding 40 (7×7 pixel window) or 56 pixels (9×9 pixel window), respectively. Detection of moderately extended objects (up to several times the PSF size) is achieved by searching the image in up to four consecutive detection runs each doubling the pixel size (parameter `nruns`, default value = 3).

Following the definition which was, e.g., used by the ROSAT mission, detection likelihoods (per energy band and total) are given for each source in the form $L = -\ln p$ where p is the probability of Poissonian random fluctuation of the counts in the detection cell which would have resulted in at least the observed number of source counts. The value of p is calculated as a function of raw source counts and raw background counts in the detection box (see `eboxdetect` task description for further info on the detection algorithm).

The local mode sliding box source detection is performed executing the following command:

```
eboxdetect usemap=no likemin=8 withdetmask=yes detmasksets=mask.fits \
           imagesets='image_b1.fits image_b2.fits image_b3.fits \
                      image_b4.fits image_b5.fits' \
           expimagesets='image_b1exp.fits image_b2exp.fits image_b3exp.fits \
                         image_b4exp.fits image_b5exp.fits' \
           pimin='200 500 2000 4500 7500' pimax='500 2000 4500 7500 12000' \
           boxlistset=eboxlist_l.fits
```

The local mode detection is switched on setting `usemap=no`. It is recommended to use a detection threshold of `likemin=8` to provide a complete source list as input for `esplinemap`. Note, the parameter `ecf` will need to be specified if one already at this stage of the source detection chain is interested in the computation of source fluxes (see section on `emlselect` below).

In the next step, the task `esplinemap` makes use of the `eboxdetect` generated local mode source list to derive spline background maps from the non-source regions. Sources found in the local detection step at significance levels (column SIGMA of the source list) exceeding a user-specifiable threshold (input parameter `mlmin`) are removed from the image using a suitable PSF and source brightness dependent cut-out radius (determined to be the radius at which each source contributes more than a user-specifiable number of counts/arcsec^2 to the background; parameter `scut`):

```
esplinemap bkgimageset=image_b1bkg.fits imageset=image_b1.fits \
           boxlistset=eboxlist_l.fits scut=0.005 nsplinenodes=16 \
           withdetmask=yes detmaskset=mask.fits \
           withexpimage=yes expimageset=image_b1exp.fits
```

This commands needs to be performed for all energy bands (b1 to b5) separately. An optionally diagnostic output photon image where sources have been masked out (the so called cheesed image) can be created setting `withcheese=yes` and defining the name of the cheesed image via `cheeseimageset`. In addition, `esplinemap` is able to determine the background caused by OoT events registered during the readout process of the pn CCDs (§ 4.9). If the flag `withootset` is set, the photon event table specified in `ooteventset` is read and the background caused by OoT events is included in the output background map.

To improve the detection sensitivity reached before with the local mode detection, the sliding box source detection now should be performed in map mode (`usemap=yes`). Here the background will be taken from the background maps that were determined by `esplinemap`:

```
eboxdetect usemap=yes likemin=8 withdetmask=yes detmasksets=mask.fits \
           imagesets='image_b1.fits image_b2.fits image_b3.fits \
                      image_b4.fits image_b5.fits' \
           expimagesets='image_b1exp.fits image_b2exp.fits image_b3exp.fits \
                         image_b4exp.fits image_b5exp.fits' \
           bkgimagesets='image_b1bkg.fits image_b2bkg.fits image_b3bkg.fits \
                         image_b4bkg.fits image_b5bkg.fits' \
           pimin='200 500 2000 4500 7500' pimax='500 2000 4500 7500 12000' \
           boxlistset=eboxlist_m.fits
```

The next step is to generate the final source list with the task `emldetect`: a simultaneous maximum likelihood PSF fit is performed to the source count distribution in all energy bands of each involved EPIC telescope with the following free parameters: source location (RA, Dec), source extent (Gaussian sigma) and source count rate. Source location and extent are constrained to the same best-fit value in all energy bands whereas count rates are the best-fit values in each band. The PSF fitting may either be performed in single source (default) or in multi-source mode (parameter `nmaxfit` > 1). Unless `nmaxfit` > 1, `emldetect` will not detect new sources, but characterizes the detected sources by making a PSF fit. Energy conversion factors (ECFs) can be supplied for a conversion of source count rates into flux values. The ECFs for each energy band depend on the pattern selection and the filter used during the observation (see the XMM-Newton Serendipitous Source Catalogue User Guide for the list of the ECFs values used in the processing of the XMM-Newton Serendipitous Source Catalogue [2]). Here, a pn thin filter observation where patterns 0 - 4 are considered, is assumed (note that the ECF values used in the example below are just illustrative):

```
emldetect imagesets='image_b1.fits image_b2.fits image_b3.fits \
                     image_b4.fits image_b5.fits' \
          expimagesets='image_b1exp.fits image_b2exp.fits image_b3exp.fits \
                        image_b4exp.fits image_b5exp.fits' \
          bkgimagesets='image_b1bkg.fits image_b2bkg.fits image_b3bkg.fits \
                        image_b4bkg.fits image_b5bkg.fits' \
          pimin='200 500 2000 4500 7500' pimax='500 2000 4500 7500 12000' \
          boxlistset=eboxlist_m.fits \
          ecf='10.596 6.816 2.054 0.995 0.259' \
          mlmin=10 mllistset=emllist.fits
```

Especially in cases where an expected X-ray source is not detected by the source detection steps described above, the user might be interested in using task `esensmap` to generate a sensitivity map giving (rough) point source detection upper limits (vignetting corrected source count rate corresponding to the likelihood of detection as specified in the parameter file) for each image pixel. The task `esensmap` may either be called for individual energy bands or combinations of energy bands and instruments. The upper limits are calculated by assuming Poissonian count statistics in each 3×3 pixel detection cell, using the exposure and background values read from the input images. In the case of multiple input energy bands the upper limits are expressed in units of counts per seconds for the combined band (i.e. they refer to the detection sensitivity which would be achieved by adding up the photons observed in the individual bands). Below, an example on how to compute a sensitivity map for a single energy band is given:

```
esensmap expimagesets=image_b1exp.fits bkgimagesets=image_b1bkg.fits \
         detmasksets=mask.fits mlmin=10 sensimageset=image_b1sen.fits
```

This command eventually should be performed for all energy bands (b1 to b5) separately.

Alternatively, if one is interested in a sensitivity map for the combined energy range, the command to be issued could be:

```
esensmap expimagesets='image_b1exp.fits image_b2exp.fits image_b3exp.fits \
                       image_b4exp.fits image_b5exp.fits' \
         bkgimagesets='image_b1bkg.fits image_b2bkg.fits image_b3bkg.fits \
                       image_b4bkg.fits image_b5bkg.fits' \
         detmasksets=mask.fits mlmin=10 sensimageset=image_sen.fits
```

4.12.3.2 Running the EPIC source detection chain

Assuming that the user either wants to make use of the pipeline generated image products or that he/she has created images in different energy bands, the task `edetect_chain` can be called to perform all source detection steps described in § 4.12.3.1 via a single command.

The attitude information is assumed to be available from the file `attitude.fits` (created by the `atthkgen` task). The example below further assumes that the source detection will be performed on a background cleaned pn thin filter observation (the name of the calibrated and filtered event list being `filtered.fits`). As noted above, the ECFs for each energy band depend on the EPIC camera, the pattern selection and the filter used during the observation (see XMM-Newton Serendipitous Source Catalogue User Guide [2]).

The complete EPIC source detection chain is started with the following command (note that the ecf values used in the example below are just illustrative):

```
edetect_chain eventsets=filtered.fits attitudeset=attitude.fits \
              imagesets='image_b1.fits image_b2.fits image_b3.fits \
                         image_b4.fits image_b5.fits' \
              pimin='200 500 2000 4500 7500' pimax='500 2000 4500 7500 12000' \
              ecf='10.596 6.816 2.054 0.995 0.259' \
              eboxl_list=eboxlist_l.fits eboxm_list=eboxlist_m.fits \
              esp_nsplinenodes=16 eml_list=emllist.fits esen_mlmin=10
```

After completion of the `edetect_chain` task, the following output files have been created: exposure maps (from task `eexpmap`), detector mask images (from task `emask`), background maps (from task `esplinemap`), `eboxdetect` source list (local mode), `eboxdetect` source list (map mode), `emldetect` source list, source maps, if `eml_withsourcemap=yes` (from task `emldetect`) and sensitivity maps (from task `esensmap`).

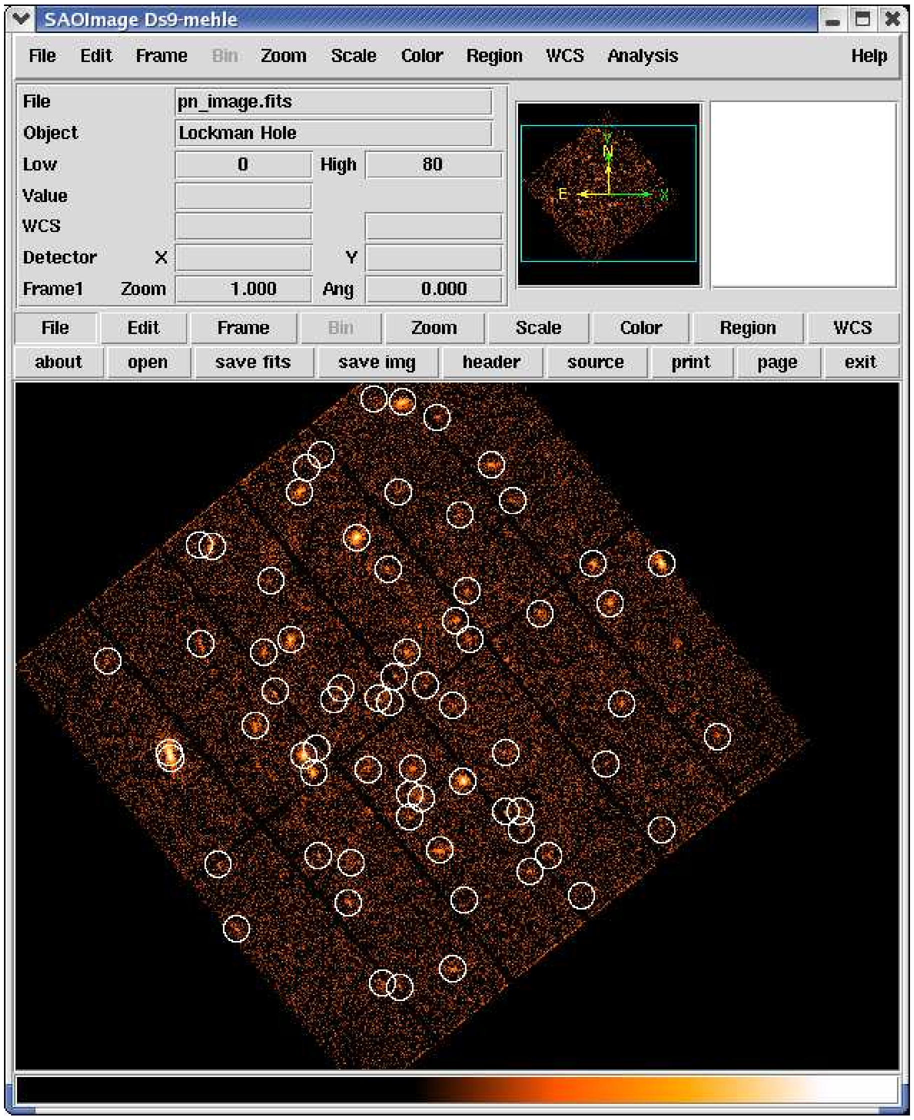
To verify the quality of the performed source detection, the user might want to check generated maps with the image viewer programme `ds9`. In addition, the task `srcdisplay` can be used to overlay all the detected source lists onto an image. Circles are used to depict the source positions. The radius of these circles can be set (in degrees) using the `sourceradius` parameter. An optional ID label can also be displayed, corresponding to the row number of that source in the input source list. This can be enabled through the `uselabel` parameter. Plotting the ID helps the user to refer back to source properties documented in the source list.

As the plotted circles are in fact `ds9`-type regions, they can be written out to a file for future use (for example, when running a later `ds9` session) by setting `withregionfile` to true, and specifying the desired file name via the `regionfile` parameter (set to `regionfile.txt` by default).

To show e.g. the generated merged source list overlaid onto an EPICimage (called `pn_image.fits` in the example) the following command can be issued:

```
srcdisplay boxlistset=emllist.fits imageset=pn_image.fits sourceradius=0.01
```

Figure 38 shows an example of such a `srcdisplay` run.



File	pn_image.fits		
Object	Lockman Hole		
Low	0	High	80
Value			
WCS			
Detector X		Y	
Frame1 Zoom	1.000	Ang	0.000

Figure 38: Resulting ds9 display of a `srcdisplay` command issued to overlay a final source list onto a pn image.

5 Analysis of RGS spectrometer data

The SAS provides a number of tools for analysis of data from the RGS1 and RGS2 spectrometers, starting from the raw data in the ODF and finishing with one or more high-resolution X-ray spectra and their associated RMF response matrices and background spectra. The RGS meta-task `rgsproc`, which runs all the way from ODF to RMF, is broken down into a sequence of component tasks that deal with successive stages of the work required, allowing the user flexibility to make adjustments where necessary. While it is possible simply to type `rgsproc` at the command line and get reasonable results, the investment of some thought and advanced planning usually gives significant improvement in the quality of the final products. Help is available through the SAS on-line help system:

`http://xmm-tools.cosmos.esa.int/external/sas/current/doc/packages.rgs.html`

of which the `rgsproc` entry is a suitable RGS starting point:

`http://xmm-tools.cosmos.esa.int/external/sas/current/doc/rgsproc/index.html`.

Detailed descriptions of the methods used and parameter specifications are given there and liberal use of those pages is recommended. As a complement to this SAS manual chapter, RGS data analysis threads at `http://www.cosmos.esa.int/web/xmm-newton/sas-threads` [32] and the RGS chapter of the NASA/GSFC ABC guide [25] may also be consulted.

In common with the vast majority of XMM-Newton data [29], RGS files are in FITS format so that it is useful to have at hand general-purpose tools such as FTOOLS including `fv` [26] in particular to inspect files. The spectra and response matrices that are the final products of the RGS SAS procedures are intended for further analysis outside the SAS with standard tools such as `Xspec` [28], `SPEX` [19] or `ISIS` [21].

The results of an automatic version of `rgsproc` that is run on all ODFs are available via the XSA. These automatically generated results, known as the PPS products, are discussed in § 5.19 below. Naturally, these procedures are run without human intervention and thus are not expected to emulate the quality that can often be produced by the individual attention of a well-informed and creative astronomer. Experience shows, however, that they are useful, especially when used in conjunction with the other XMM-Newton instruments. It is most likely the case, though, that an RGS observer will benefit from running the analysis again starting from the ODF. This chapter is organised roughly along the lines of a typical session of RGS work.

Immediately, the most important things to be considered are

- the source coordinates,
- the source extent,
- the behaviour of the background, and
- the calibration data

and RGS analysts should make explicit decisions about each of these things for every single observation on which they work.

5.1 Source coordinates

RGS data are individual events. The wavelength, λ, assigned to a photon of spectral order m is determined by the diffraction equation

$$m\lambda = d(\cos\beta - \cos\alpha)$$

where d is the grating spacing. The dispersion angle β is fixed by the photon's position on the CCD detector and the constant geometry of the detector and grating assemblies. The only remaining variable, therefore, is α, the angle of incidence of light on the gratings so that the X-ray photon wavelength reduces to a function of the source celestial coordinates $RA(J2000), DEC(J2000)$ only:

$$\lambda = \lambda(\alpha) = \lambda(RA(J2000), DEC(J2000))$$

and it is the analyst's responsibility to make sure that they are as accurate as possible. Differentiation of the diffraction equation shows that a systematic error of up to 2.3 mÅ is introduced for every arcsecond error in the source coordinates. The PPS procedure makes an automatic choice between the proposal's pointing coordinates and X-ray coordinates derived from the simultaneous EPIC images, both of which have been known to be unreliable for a number of reasons. It is therefore worthwhile to take as much care as possible over the coordinates used in the analysis including proper motion as necessary. The SIMBAD [22] and NED [23] reference databases are excellent in this regard. The source coordinates required by `rgsproc` are thus best explicitly supplied by the analyst in decimal degrees to six decimal places, wherever possible. In the absence of any better information, the proposal pointing coordinates are used by default.

5.2 Source extent

The SAS is easy to use for a single dominant point source in the RGS apertures. In this case, the PPS procedure is also successful most of the time. The means also exist to treat more complex source configurations and, with proper care, both multiple point sources and extended sources may be tackled as discussed in below in § 5.9 and § 5.10 respectively. The PPS products are of limited use in these circumstances.

5.3 Background behaviour

The instrumental background also requires attention, particularly because of its variability. Most of the time the background is low enough for the RGS to be more-or-less photon limited for the detection of point-source spectra over most of its bandwidth once the proper event selections have been made. However, solar flares and other particle events have caused changes of two or more orders of magnitude in the background rate on time scales short in comparison with the typical length of an observation. In such cases the signal spectrum can be completely swamped but an entire observation is seldom affected. It is imperative, therefore, to make an assessment of the background's behaviour during an observation and exclude any periods that are too badly contaminated following, for example, the procedure described below in § 5.7.2.

5.4 Calibration data

In order to derive physical parameters from the data in an observation, the SAS uses the RGS instrument model encapsulated in the calibration data stored in the CCF. These data are not supplied with the ODF or PPS products but are available for immediate download [30], along with procedures to ensure your calibration data remain up-to-date and the latest instrument news [31]. The CCF is an accumulation of all the calibration data ever released so that one of the initial SAS tasks is to use the task `cifbuild` to build a calibration index file `ccf.cif` that enumerates which CCF components apply to an observation. A more complete discussion of these matters appears elsewhere in this manual in § 2.3.3 and § 3.11.

5.5 Taking delivery of RGS data

It is a good idea to adopt a systematic naming scheme for a hierarchy of XMM-Newton directories in which to store and distinguish raw ODF data, pipeline PPS products, and in this case RGS files of your own making. For example, when dealing with the Mkn421 observation with ID 0136540101 in revolution 259 appropriate directories might be called,

```
/data/XMM/0136540101/ODF

/data/XMM/0136540101/PPS

/data/XMM/0136540101/RGS
```

These directories will be used in some examples below. After your XMM-Newton data have been downloaded from the archive, the contents of the data package should be verified with reference, should the need arise, to the XMM-Newton Data File Handbook [29] which contains details of the structure of all XMM-Newton files.

5.5.1 Raw RGS Data Files in the ODF

Raw data of all seven XMM-Newton instruments, including RGS1 and RGS2, are to be found in a single directory `/odf`. If the delivery includes data from more than one observation, there will be a separate directory for each. The ODF names for RGS data are as follows:

- mmmm_iiiiiijjkk_aabeeeccfff.zzz, where
  - *mmmm*: revolution orbit number
  - *iiiiiijjkk*: observation number
  - *aa*: detector ID (R1 - RGS1, R2 - RGS2, SC - XMM-Newton spacecraft)
  - *b*: flag for scheduled (S) or unscheduled (U) observations, or (X) for general use files
  - *eee*: exposure number within the observation or ”000”
  - *cc*: CCD identifier or ”00”
  - *fff*: data identifier shown in Table 6
  - *zzz*: Format (FITS - FIT, ASCII - ASC)

Data Identifier	Contents
RGS related files	
AUX	On-board processing statistics
SPE	Raw event list for one CCD
DII	Diagnostic images
D1H/D2H	CCD readout settings
PFH	Housekeeping data
ODX	Pixel offset data
OFX	Offset file
XMM-Newton related files	
ATS	Spacecraft attitude history

Table 6: ODF data file identifiers relevant for RGS analysis.

5.6 Running the RGS processor `rgsproc`

The work done by `rgsproc`,

`http://xmm-tools.cosmos.esa.int/external/sas/current/doc/rgsproc/index.html`

falls into two main parts: first the construction of a calibrated event list, and second the selection of events to be accumulated into spectra for one or more of the entries in a source list. Event construction starts from the spatial coordinates and pulse heights among the 6 columns of raw readout data stored in one file for each CCD and ends with 17 calculated columns in one merged file for each RGS. A CCD delivers a few hundred thousand events in a typical observation and the merged file contains, therefore, perhaps a few million before event selection begins. The final selected event file can contain less than half of the merged events after exclusion of hot pixels and columns, although after the RGS instruments were cooled in November 2002 the hot stuff became much less numerous. Evidently, the rejection of hot columns and pixels is a fundamental part of the analysis. The further selection of events for source and background spectra then depends on the position of the source within the RGS apertures as determined by its coordinates held in the source list and the extent of the source and background selection regions chosen explicitly or by default.

Here is an example `rgsproc` run on Mkn421 using accurate NED source coordinates in the directory scheme discussed above. As discussed in detail in § 2.3, the environment variables `SAS_CCFPATH`, `SAS_ODF` and `SAS_CCF` supply the SAS with calibration and data information so that `rgsproc`, which always writes its output files to the working directory, may be run in any location.

```
setenv SAS_CCFPATH /path/to/<CCF>
setenv SAS_CCF /path/to/<ODF>
setenv SAS_ODF /path/to/<ODF>
cifbuild
setenv SAS_CCF /path/to/<ODF>/ccf.cif
odfingest
setenv SAS_ODF /path/to/<ODF>/[rev]_[obsid]_SCX00000SUM.SAS
```

```
cd $SAS_ODF
mkdir RGS
cd RGS
rgsproc withsrc=yes srclabel=Mkn421 \
                    srcstyle=radec srcra=166.113808 srcdec=+38.208833
```

The task `odfingest` needs only to be run once after receipt of the ODF, while a new `ccf.cif` calibration index file should be regenerated with `cifbuild` whenever a new relevant CCF component is available. `rgsproc` has about a hundred potentially adjustable parameters, see `http://xmm-tools.cosmos.esa.int/external/sas/current/doc/rgsproc/node26.html`

In this case, the source coordinates only have been specified, leaving all other parameters at their default values, some of the more important of which are shown in Table 7.

parameter	default value
`entrystage`	`1:events`
`finalstage`	`6:lightcurve`
`orders`	1 2
`withdiagoffset`	`true`
`spectrumbinning`	`lambda`
`lambdabinref`	4.005 angstrom
`lambdabinwidth`	0.010 angstrom
`nlambdabins`	3600
`xdispbinning`	`binSize`
`xdispbinref`	−0.0009126 radians
`xdispbinwidth`	+0.0000108 radians
`nxdispbins`	170
`bkgcorrect`	`no`
`keepcool`	`yes`
`rejflags`	BAD_SHAPE ON_BADPIX NEXT_TO_BADPIX BELOW_ACCEPTANCE NEXT_TO_CCD_BORDER
`xpsfincl`	95%
`xpsfexcl`	98%
`pdistincl`	95%
`rows`	4000
`timebinsize`	1000

Table 7: Default values of key `rgsproc` parameters.

As it is running, `rgsproc` gives regular messages about its progress, although these are not designed to prompt any action except in the unlikely event of error. The final outcome, as shown in table 8, is a set of 16 FITS files for each RGS consisting of

- 2 event lists
- 1 source list

- 2 lists of good time intervals
- 1 exposure map
- 3 1st order spectral files
- 3 2nd order spectral files
- 4 light curves

and 3 other general-purpose FITS files. Source spectra are not background corrected by default so that the corresponding background spectra must explicitly be included in subsequent analysis with `Xspec` for example.

The RGS files have names of the form

- P0136540101RnSxpxCCCCCCm003.FIT, where

  0136540101 is the observation number;
  Rn is R1 for RGS1 or R2 for RGS2;
  xxx is the exposure number, 001 for RGS1 or 002 for RGS2 in this case;
  CCCCCC is the product type;
  m is the negative order number, 1 and 2 by default;
  003 is the number in the SRCLI list of sources.

If a file does not apply to a particular exposure, *Sxxx* is replaced by *X000*. Similarly, *0* and *000* show that the order and source number, respectively, are deemed irrelevant.

5.6.1 Events, sources and selection criteria

In the default spectroscopy mode, the most important parameters for each detected photon in the event lists are the two spatial coordinates and one energy coordinate. These go through a series of improvements in the initial stages of `rgsproc` in which the initial raw set of,

```
[CCDNR, CCDNODE, RAWX, RAWY, ENERGY]
```

is transformed using the detailed geometry of the grating and detector assembles into coordinate angles along the grating dispersion direction, β or `BETA`, and the perpendicular cross-dispersion direction, χ or `XDSP`,

```
[BETA, XDSP, PHA]
```

which, in turn, are combined with knowledge of the history of the spacecraft's pointing and CCD gain and CTI characteristics to yield,

```
[BETA_CORR, XDSP_CORR, PI]
```

in units of radians, radians and eV respectively. The detectors are almost invariably read out using a method which combines a 3×3 area of original CCD pixels into a single value, so-called 3×3 on-chip binning or OCB. `BETA_CORR` and `XDSP_CORR` reconstruct the angular distribution of photons emerging from the gratings and include randomisation of the quantised CCD coordinates in order to simulate a continuous distribution. The coordinates of the nominated source make a subtle appearance at this stage as they are used in the correction of `BETA` to `BETA_CORR` (and hence to `MLAMBDA`) caused by variations in the angle of incidence on the gratings due to spacecraft pointing jitter. The otherwise redundant `PI` energy column is used to distinguish between spatially overlapping orders.

Once the event list has been filtered for bad pixels of the various types signaled by `rejflags` in Table 7, the source list plays a central role. The source list here has 5 binary-table extensions,

```
P0136540101R2S002SRCLI_0000.FIT:SRCLIST            1=PROPOSAL 2=ONAXIS 3=MKN421
P0136540101R2S002SRCLI_0000.FIT:RGS2_BACKGROUND    LAMBDA-XDSP_CORR region
P0136540101R2S002SRCLI_0000.FIT:RGS2_SRC3_SPATIAL  LAMBDA-XDSP_CORR region
P0136540101R2S002SRCLI_0000.FIT:RGS2_SRC3_ORDER_1  LAMBDA-PI region
P0136540101R2S002SRCLI_0000.FIT:RGS2_SRC3_ORDER_2  LAMBDA-PI region
```

which specify selection regions for the nominated source #3 and the orders 1 and 2 chosen by default and the background region. The calculation of the position and width of the selection regions depends on the source's celestial coordinates, and the fractions of the `XDSP_CORR` and `PI` response curves specified by the parameters `xpsfbelow`, `xpsfabove`, `xpsfexcl` and `pdistincl`. The events which contribute to source and background spectra are those that fall in selection regions defined, for example, for 1st order in RGS2 :

```
   (MLAMBDA,PI) IN REGION(P0136540101R2S002SRCLI_0000.FIT:RGS2_SRC3_ORDER_1))
&& ((MLAMBDA,XDSP_CORR) IN REGION(P0136540101R2S002SRCLI_0000.FIT:RGS2_SRC3_SPATIAL))
```

Finally, the simulated continuous `MLAMBDA` distribution of selected events are rebinned into channels to yield the final binned counts spectra. Before SAS v8.0, spectra were always accumulated in intervals of the dispersion angle `BETA_CORR`. Starting in SAS v10.0, spectra are calculated by default on a uniform wavelength grid. Wavelength-based spectra facilitate the combination of two or more spectra and their associated background and response files.

5.6.2 Pixel-by-pixel offset subtraction

One of the standard procedures applied during `rgsproc` is a so-called offset correction which is designed to deal with an additive noise property of CCDs. While it is possible to use an identical value for every pixel in a CCD node, since SAS v6.0, an alternative was offered that takes advantage of offset values determined for each individual pixel from routine instrumental monitoring data. These offset data, which form part of the ODF, are accumulated every 3 revolutions thus also providing each pixel with its offset history. Experience of this alternative approach has confirmed the advantages described in trials (see Technical report XMM-SOC-CAL-TN-0046 [33]) and it has become the default method.

For comparison, the original offset method could be selected with the `withdiagoffset` switch as in the following example :

```
rgsproc withsrc=yes srclabel=Mkn421 \
                    srcstyle=radec srcra=166.113808 srcdec=+38.208833 \
                    withdiagoffset=no
```

5.6.3 The class of cool pixels

Hot pixels and columns are a routine feature of CCD detectors and `rgsproc` takes action to exclude them from the spectra it generates. The accumulation of nearly 1 million seconds data on the bright blazar Mkn421 over the course of the mission has allowed a class of cool pixels to be identified. These are single columns that give signals a few percent below the values expected from their immediate neighbours and are only likely to be relevant when studying weak absorption features in spectra with high statistics. By default, `rgsproc` does not discard these data but they can be excluded using the `keepcool` switch as in the following example:

```
rgsproc withsrc=yes srclabel=Mkn421 \
                    srcstyle=radec srcra=166.113808 srcdec=+38.208833 \
                    keepcool=no
```

5.7 The use of `xmmselect` on RGS data

Although the spectra and response matrices produced by `rgsproc` are usually trustworthy, it is worthwhile getting to know the events files on which they are based as well as making routine checks on the data. As its name suggests, `xmmselect`

`http://xmm-tools.cosmos.esa.int/external/sas/current/doc/xmmselect`

is a tool for the manipulation and display of XMM-Newton data in general, including RGS event files, via a GUI:

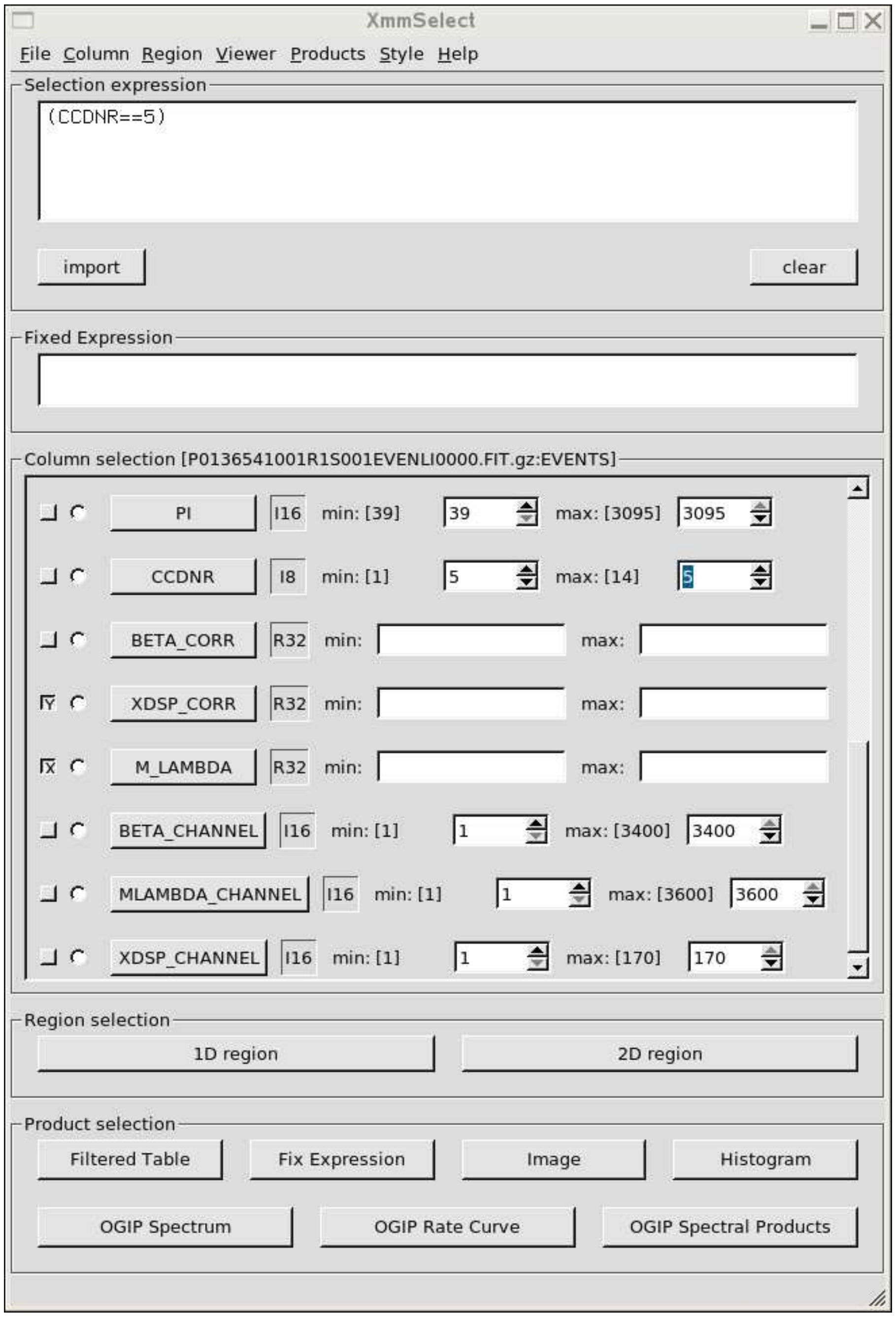
```
xmmselect table=P0136540101R1S001EVENLI0000.FIT:EVENTS
```

to provide a graphical interface to `evselect`, its command-line equivalent.

Fig. 39 illustrates the main panel of `xmmselect` in use on an RGS1 event list. It is possible to specify both simple selection criteria, such as the one shown there, or the more complex RGS spectrum regions discussed above in § 5.6.1 before making an image, for example. For every operation, `xmmselect` displays the results and writes them to an appropriate standard-format FITS file. The displays are done by launching automatically one of several third-party graphical tools, such as `ds9` [27], that allow a great deal of flexibility in tailoring plots to individual requirements.

As a matter of routine, it is advisable to look at `MLAMBDA/XDSP_CORR` and `MLAMBDA/PI` plots of the screened event list and to the source and background light curves to be able to make a critical assessment of the

- overall strength of the spectral orders
- quality of the selection regions

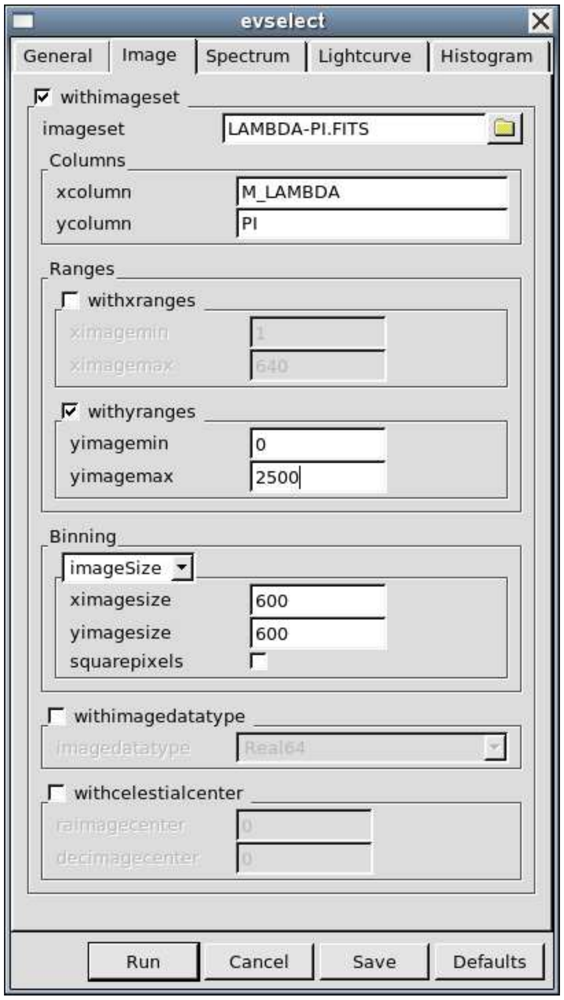


```
(CCDNR==5)
```

☐	PI	I16	min: [39]	39	max: [3095]	3095
☐	CCDNR	I8	min: [1]	5	max: [14]	5
☐	BETA_CORR	R32	min:		max:	
☒	XDSP_CORR	R32	min:		max:	
☒	M_LAMBDA	R32	min:		max:	
☐	BETA_CHANNEL	I16	min: [1]	1	max: [3400]	3400
☐	MLAMBDA_CHANNEL	I16	min: [1]	1	max: [3600]	3600
☐	XDSP_CHANNEL	I16	min: [1]	1	max: [170]	170

Figure 39: A common use of `xmmselect` is to inspect details of RGS data. In this example, the user has pressed the **CCDNR** button after adjusting the adjacent minimum and maximum values to select CCD 5 only. The selection criterion is then shown in the top window. Columns `MLAMBDA` and `XDSP_CORR` have been selected using the checkboxes on the left in preparation for pressing the **Image** button to produce a pointing-corrected spatial plot of the data of the single CCD selected.

- success of hot pixel detection
- source variability
- background strength and variability
- possible presence of other sources
- source spatial extent



```
[✓] withimageset
imageset            LAMBDA-PI.FITS
Columns
  xcolumn           M_LAMBDA
  ycolumn           PI
Ranges
  [ ] withxranges
    ximagemin       1
    ximagemax       640
  [✓] withyranges
    yimagemin       0
    yimagemax       2500
Binning
  imageSize
    ximagesize      600
    yimagesize      600
    squarepixels    [ ]
[ ] withimagedatatype
  imagedatatype     Real64
[ ] withcelestialcenter
  raimagecenter     0
  decimagecenter    0
```

Figure 40: The `xmmselect` Image panel is shown here for preparing a `MLAMBDA/PI` banana plot. Values have been specified for `imageset`, the image output file, and for a y-axis range suitable for the range of photon PI values. Pressing the **Run** button gets the work done.

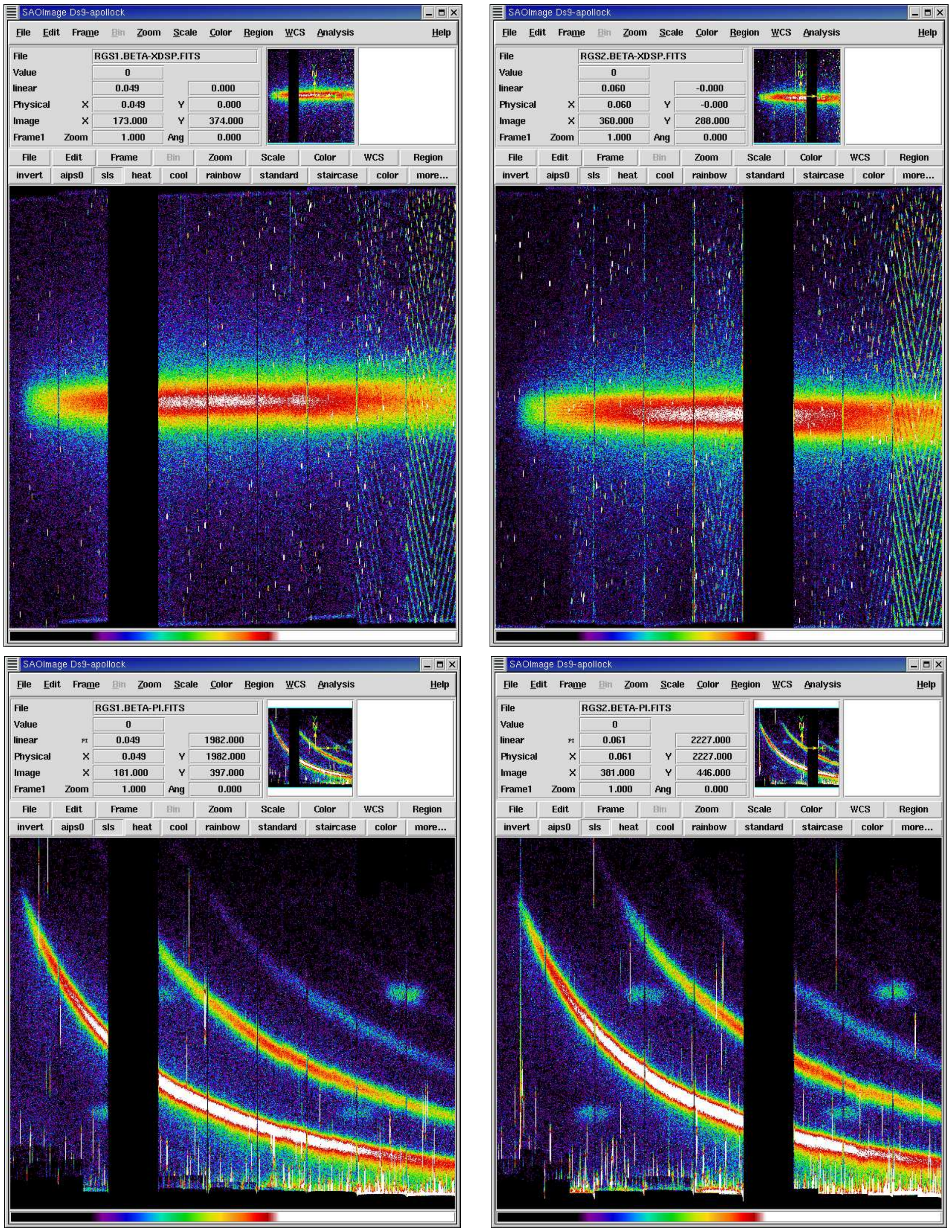
5.7.1 Generating RGS images

Once the axes have been selected and any selection criteria specified, clicking the **Image** button initiates dialogue panels that include an *Image* section like the one shown in Fig. 40 which gives the opportunity to review the choices made. The `MLAMBDA/PI` images, commonly known as banana plots, are improved by overruling the default y-range by checking the `withyranges` box and setting, e.g. `yimagemin=0`, `yimagemax=2500`.

Fig. 41 shows plots of the merged RGS1 events. These plots are orthogonal projections of the all-important `MLAMBDA,XDSP_CORR,PI` 3-D RGS data space of the merged list of all the events detected in the observation, thus showing all the features of RGS data. The edges are clear of the 9 CCDs, numbered 1-9 from right to left. In both plots, wavelength and dispersion angle increase from left to right.

File	Contents
P0136540101R1S001BGSPEC1003.FIT	RGS1 1st order background spectrum (*)
P0136540101R1S001BGSPEC2003.FIT	RGS1 2nd order background spectrum (*)
P0136540101R1S001EVENLI0000.FIT	RGS1 screened event list
P0136540101R1S001EXPMAP0000.FIT	RGS1 exposure map
P0136540101R1S001RSPMAT1003.FIT	RGS1 1st order response matrix
P0136540101R1S001RSPMAT2003.FIT	RGS1 2nd order response matrix
P0136540101R1S001merged0000.FIT	RGS1 raw merged event list
P0136540101R1S001SRCLI_0000.FIT	RGS1 source list
P0136540101R1S001SRSPEC1003.FIT	RGS1 1st order source+background spectrum
P0136540101R1S001SRSPEC2003.FIT	RGS1 2nd order source+background spectrum
P0136540101R1S001SRTSR_1003.FIT	RGS1 1st order source light curve
P0136540101R1S001BGTSR_1003.FIT	RGS1 1st order background light curve (*)
P0136540101R1S001SRTSR_2003.FIT	RGS1 2nd order source light curve
P0136540101R1S001BGTSR_2003.FIT	RGS1 2nd order background light curve (*)
P0136540101R1X000hkgti_0000.FIT	RGS1 housekeeping good time intervals
P0136540101OBX000attgti0000.FIT	RGS1 spacecraft attitude good time intervals
P0136540101R2S002BGSPEC1003.FIT	RGS2 1st order background spectrum (*)
P0136540101R2S002BGSPEC2003.FIT	RGS2 2nd order background spectrum (*)
P0136540101R2S002EVENLI0000.FIT	RGS2 screened event list
P0136540101R2S002EXPMAP0000.FIT	RGS2 exposure map
P0136540101R2S002RSPMAT1003.FIT	RGS2 1st order response matrix
P0136540101R2S002RSPMAT2003.FIT	RGS2 2nd order response matrix
P0136540101R2S002merged0000.FIT	RGS2 raw merged event list
P0136540101R2S002SRCLI_0000.FIT	RGS2 source list
P0136540101R2S002SRSPEC1003.FIT	RGS2 1st order source+background spectrum
P0136540101R2S002SRSPEC2003.FIT	RGS2 2nd order source+background spectrum
P0136540101R2S002SRTSR_1003.FIT	RGS2 1st order source light curve
P0136540101R2S002BGTSR_1003.FIT	RGS2 1st order background light curve (*)
P0136540101R2S002SRTSR_2003.FIT	RGS2 2nd order source light curve
P0136540101R2S002BGTSR_2003.FIT	RGS2 2nd order background light curve (*)
P0136540101R2X000hkgti_0000.FIT	RGS2 housekeeping good-time intervals
P0136540101OBX000attgti0000.FIT	RGS2 spacecraft attitude good time intervals
P0136540101OBX000ATTTSR0000.FIT	XMM-Newton spacecraft attitude data
P0136540101OBX000fluxed1000.FIT	Combined RGS1 & RGS2 1st order source flux spectrum
P0136540101OBX000fluxed2000.FIT	Combined RGS1 & RGS2 2nd order source flux spectrum

Table 8: Files produced by `rgsproc` for an observation of Mkn421 with default parameters except for the source name and coordinates.
(*) Not in RGS small-window mode.


SAOImage Ds9-apollock
File Edit Frame Bin Zoom Scale Color Region WCS Analysis Help
File Edit Frame Bin Zoom Scale Color WCS Region
invert aips0 sls heat cool rainbow standard staircase color more...

```
File      RGS1.BETA-XDSP.FITS
Value     0
linear      0.049        0.000
Physical  X 0.049      Y 0.000
Image     X 173.000    Y 374.000
Frame1    Zoom 1.000   Ang 0.000
```

```
File      RGS2.BETA-XDSP.FITS
Value     0
linear      0.060        -0.000
Physical  X 0.060      Y -0.000
Image     X 360.000    Y 288.000
Frame1    Zoom 1.000   Ang 0.000
```

```
File      RGS1.BETA-PI.FITS
Value     0
linear      0.049        1982.000
Physical  X 0.049      Y 1982.000
Image     X 181.000    Y 397.000
Frame1    Zoom 1.000   Ang 0.000
```

```
File      RGS2.BETA-PI.FITS
Value     0
linear      0.061        2227.000
Physical  X 0.061      Y 2227.000
Image     X 381.000    Y 446.000
Frame1    Zoom 1.000   Ang 0.000
```

Figure 41: The `MLAMBDA/XDSP_CORR` and `MLAMBDA/PI` plots produced by `xmmselect` using `ds9` for the merged RGS1 and RGS2 event lists of Mkn421 before filtering, thus showing all hot pixels and columns and other blemishes in addition to the bright smooth continuum of this active galaxy.

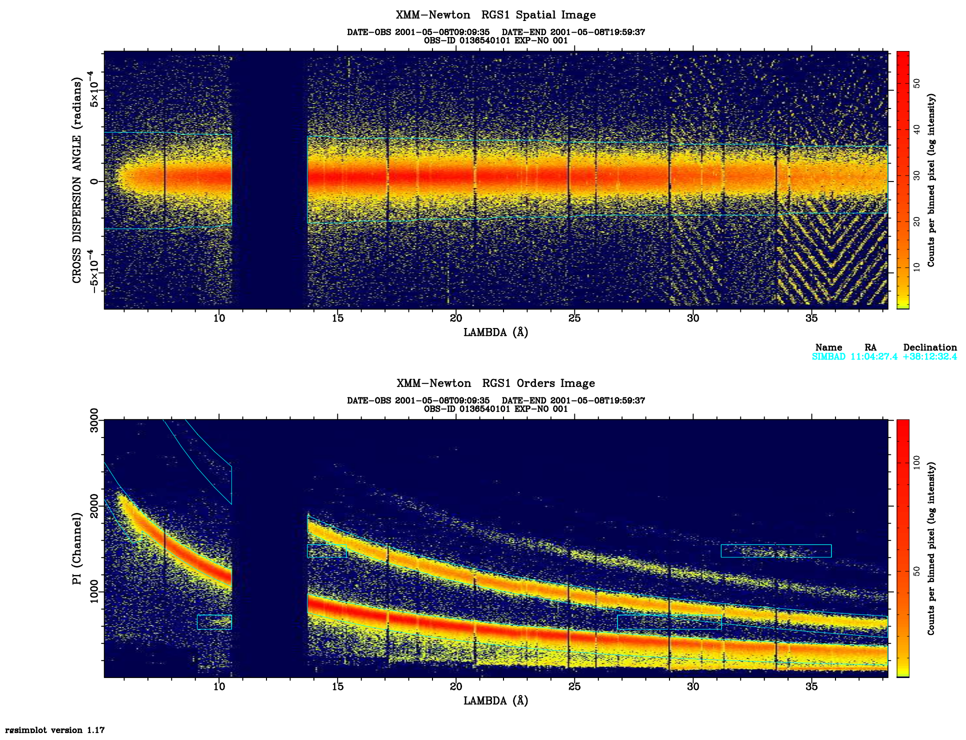


Figure 42: The MLAMBDA-XDSP_CORR and MLAMBDA-PI images produced by xmmselect from the screened event list can be shown with the selection regions using rgsimplot .

The pointing coordinates were evidently chosen well enough to put this bright source central in the aperture. The source was bright enough to be seen up to 4th or even a weak 5th order in the characteristic hyperbolic-shaped areas occupied by photons that have passed through the gratings. There are plenty of hot pixels and columns and the so-called fixed pattern noise shows as the herring-bone pattern in CCDs 1 and 2. Calibration sources of F Kα at PI= 677eV span CCDs 2&3 and 7&8 ; and Al Kα at PI= 1487eV span CCDs 3&4 and 8&9.

The locations of the selection regions may be checked using the task rgsimplot

http://xmm-tools.cosmos.esa.int/external/sas/current/doc/rgsimplot

which plots the regions over MLAMBDA-XDSP and MLAMBDA-PI images that are, in this case, most usefully generated from the screened events files. Fig. 42 shows such an example.

5.7.2 Generating raw RGS light curves to assess the background

In addition to the corrected source light curves available using the task rgslccorr described below in § 5.17, xmmselect may be used to investigate other aspects of the time variability of RGS data using the [**OGIP Rate Curve**] button with suitable selection criteria.

Perhaps the principal practical use is for assessment of the background that often accounts for the majority of detected events over the whole instrument and which must therefore be explicitly quantified. The background is made up of several contributions and is usually weak enough to cause few problems: RGS spectra are photon limited more than 80% of the time. However, solar flares and other particle events can cause significant or in rare cases even overwhelming

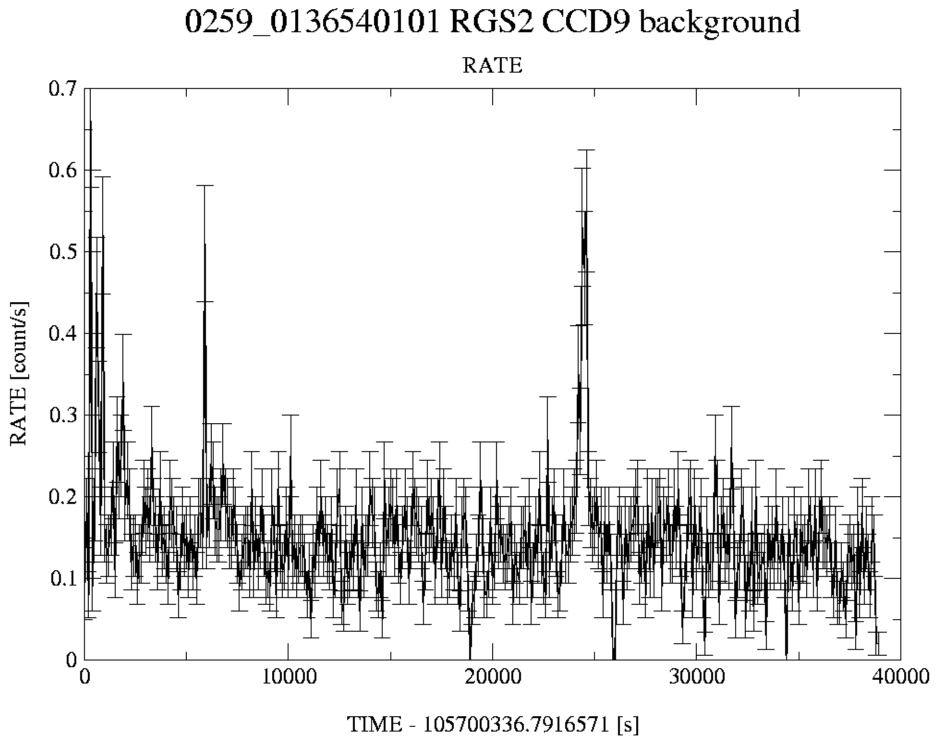


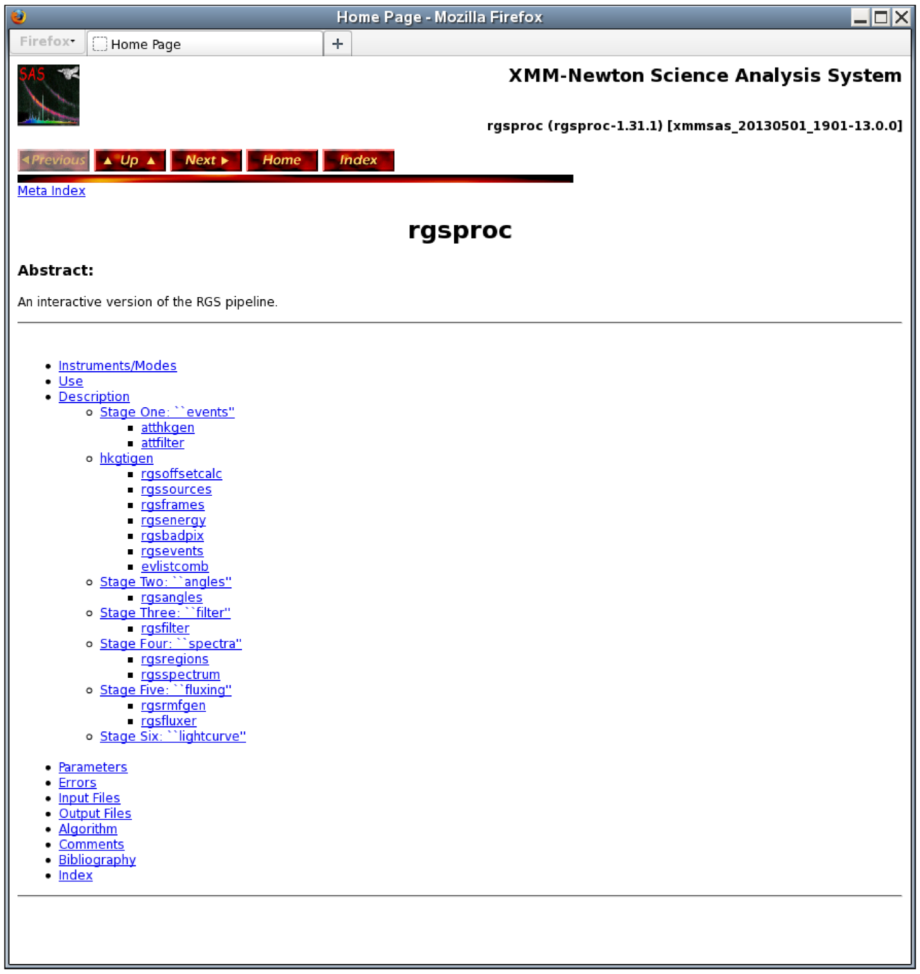
Figure 43: RGS2 light curve of the background near Mkn421 generated with `xmmselect`. Although there are a few small flares, none are bad enough to consider removing from the source data.

contamination. Rapid variability is also common so that only part of an observation may be affected so that it is possible to generate supplementary GTIs in order to exclude periods of unacceptably high background. Fig. 43 shows the background light curve generated using:

```
(CCDNR = 9) && ((MLAMBDA,XDSP_CORR) IN \
  REGION(P0136540101R2S002SRCLI_0000.FIT:RGS2_BACKGROUND))
```

What constitutes unacceptably high background is often a matter of personal judgment depending on the type of analysis undertaken. High-contrast features like strong emission lines can often tolerate higher background levels than smooth continuum spectra and the overall source brightness is clearly a consideration. It is best to experiment. As a rule of thumb, data with CCD9 background rates above 1 count/s might be considered suspect and be excluded by using the `GTI` mechanism to flag periods of low background.

```
 tabgtigen table=RGS2.background.FITS gtiset=RGS2.background.GTI.FITS \
            expression='(RATE<1)'
```



XMM-Newton Science Analysis System

rgsproc (rgsproc-1.31.1) [xmmsas_20130501_1901-13.0.0]

Meta Index

rgsproc

Abstract:

An interactive version of the RGS pipeline.

- Instruments/Modes
- Use
- Description
  - Stage One: ``events''
    - atthkgen
    - attfilter
  - hkgtigen
    - rgsoffsetcalc
    - rgssources
    - rgsframes
    - rgsenergy
    - rgsbadpix
    - rgsevents
    - evlistcomb
  - Stage Two: ``angles''
    - rgsangles
  - Stage Three: ``filter''
    - rgsfilter
  - Stage Four: ``spectra''
    - rgsregions
    - rgsspectrum
  - Stage Five: ``fluxing''
    - rgsrmfgen
    - rgsfluxer
  - Stage Six: ``lightcurve''
- Parameters
- Errors
- Input Files
- Output Files
- Algorithm
- Comments
- Bibliography
- Index

Figure 44: The `rgsproc` home page in the SAS on-line help system, showing the six stages which form the possible start and end points of RGS data analysis.

5.8 Rerunning the RGS processor `rgsproc`

As many of the quality checks described above can only be done after an initial run of `rgsproc`, a decision will be often be made to rerun the analysis with some adjustments. It might not be necessary to rerun the whole of `rgsproc`, which is divided into six different stages that are alternative entry and exit points. Fig. 44 lays out how individual tasks are grouped within the six stages. For example, the background `GTI` file made above would properly be incorporated at the filter stage as follows

```
rgsproc auxgtitables=RGS2.background.GTI.FITS \
          entrystage=3:filter finalstage=6:lightcurve
```

A similar approach could be used to generate spectra as a function of intensity using the source light curve of Fig. 48. Other examples involving further runs of `rgsproc` for multiple or extended sources are discussed below.

5.9 Treatment of multiple RGS sources

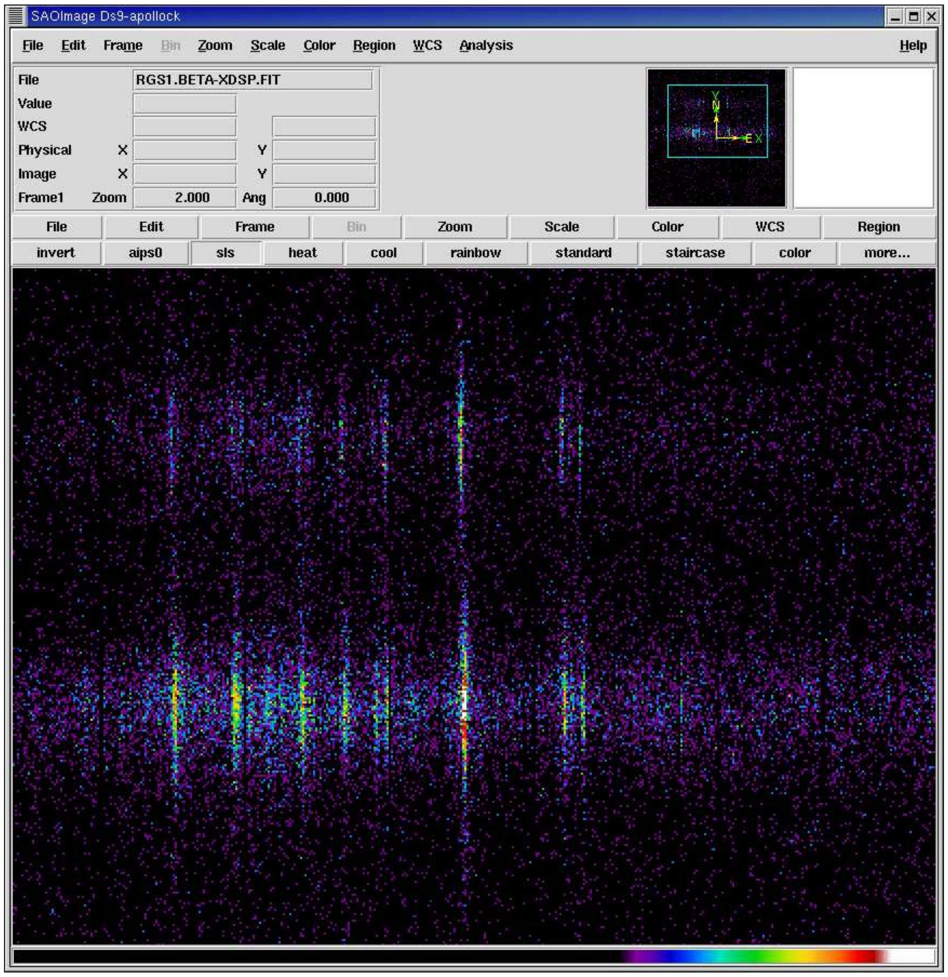

SAOImage Ds9-apollock
File Edit Frame Bin Zoom Scale Color Region WCS Analysis Help
File RGS1.BETA-XDSP.FIT
Value
WCS
Physical X Y
Image X Y
Frame1 Zoom 2.000 Ang 0.000
File Edit Frame Bin Zoom Scale Color WCS Region
invert aips0 sls heat cool rainbow standard staircase color more...

Figure 45: An example of two sources in the RGS aperture. In this observation of YY Gem and Castor, it was already known from previous work that the two stars are bright, so the aperture was aligned perpendicular to the line joining the stars to allow maximum separation of the two spectra.

In the rare cases when two or more sources appear in the RGS aperture, `rgsproc` should be instructed to calculate the required number of spectra and modify its treatment of the background. In all such cases encountered so far, such as the observation of the active stars YY Gem and Castor shown in Fig. 45, the spectra have been well enough separated so that their selection regions can be treated independently. The current tools do not allow simultaneous estimates of overlapping spectra. It is not possible initially to specify more than one source, so a step-by-step approach is required adding sources one at a time with `rgssources` and setting source and background parameters accordingly before rerunning `rgsproc` to recalculate the spectra. Having accurate SIMBAD [22] coordinates for the brighter YY Gem and weaker Castor (not forgetting Castor's high proper motion), the sequence of events might be as follows to make spectra for both stars and exclude both from the background

```
rgsproc withsrc=yes srclabel=YYGem \
                    srcstyle=radec srcra=113.655858 srcdec=+31.869386

rgssources srclist=P0123710201R1S004SRCLI_0000.FIT addusersource=yes \
           label=Castor ra=113.649428 dec=+31.888276

rgssources srclist=P0123710201R2S005SRCLI_0000.FIT addusersource=yes \
           label=Castor ra=113.649428 dec=+31.888276

rgsproc entrystage=4:spectra procsrcsexpr='INDEX==3||INDEX==4' \
                             exclsrcsexpr='INDEX==3||INDEX==4'
```

5.10 Treatment of extended RGS sources

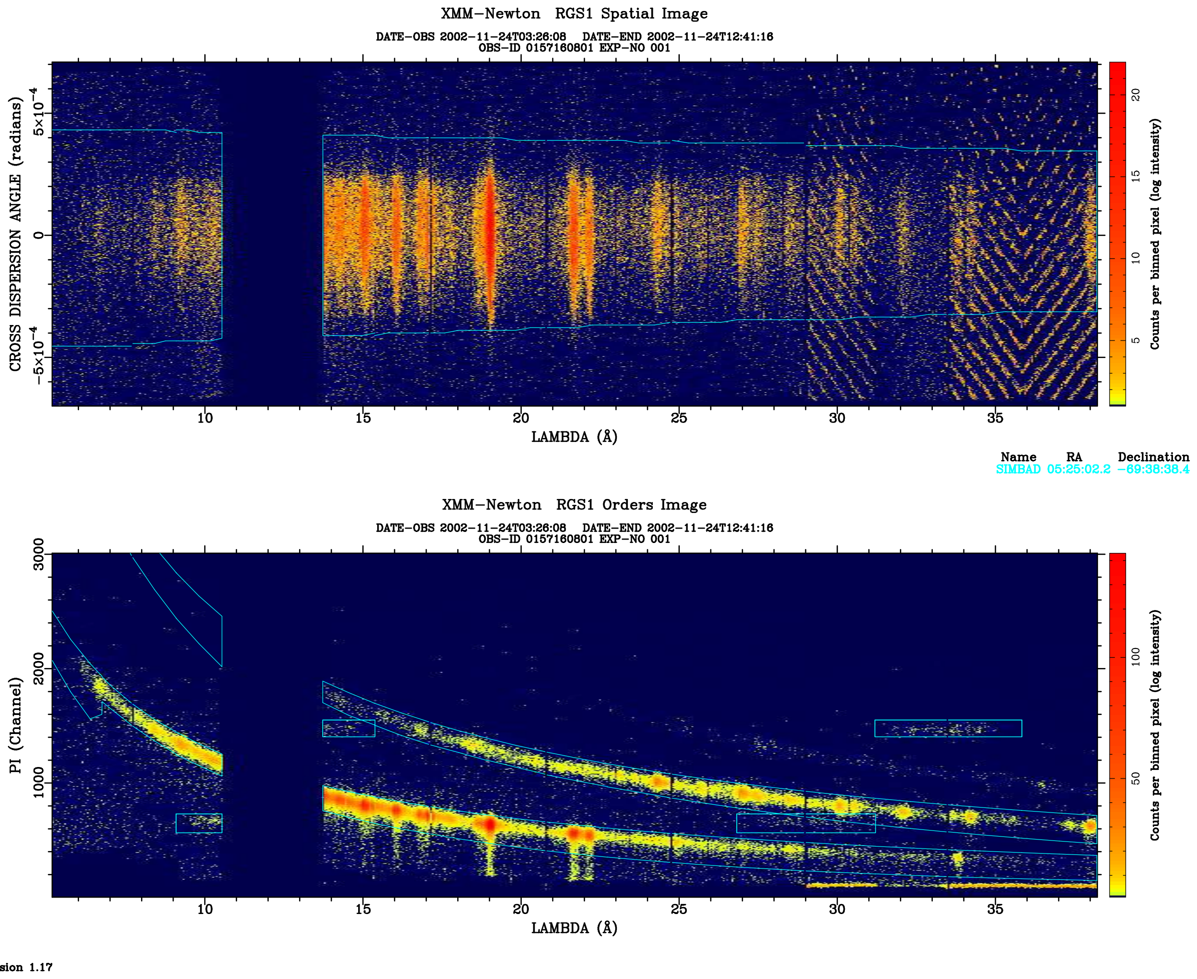


Figure 46: The bright emission lines of the SNR N132D, which is about 2 arcmin in diameter, fit comfortably within the RGS aperture but overflow the default selection regions defined for point sources. By extending the cross-dispersion selection region to 98%, in this case, most of the source flux is recovered.

Even though the methods currently used by `rgsproc` were designed for point sources, the 5 arcmin cross-dispersion width of the RGS apertures also makes the instrument suitable for observing extended sources such as supernova remnants or clusters of galaxies. Obviously, such objects can fill part or all of the aperture and invalidate the usual means of differentiating source and background selection regions in terms of the parameters `xpsfincl` & `xpsfexcl` that are defined in terms or point-source fractions. For moderately extended sources which do not fill the aperture, such as the LMC SNR N132D shown in Fig. 46, it is possible to adjust the equivalent point-source fractions by a process of trial and error to nominate suitable selection regions. For more extensive sources, when this is not possible, there are RGS background template files and techniques available through the XMM web pages that allow independent estimates of background spectra. Source extension in the dispersion direction causes confusion with the wavelength scale. Since version v11.2, `Xspec` [28] contains a new `rgsxsrc` model which specifically deals with spectra of extended sources.

5.11 Computing a model spectrum of the RGS background

The task `rgsbkgmodel` can be used to compute a model spectrum of the RGS background applicable to a given observation from a combination of observations of empty fields.

For a detailed description of this task see the technical note XMM-SOC-CAL-TN-0058 at:

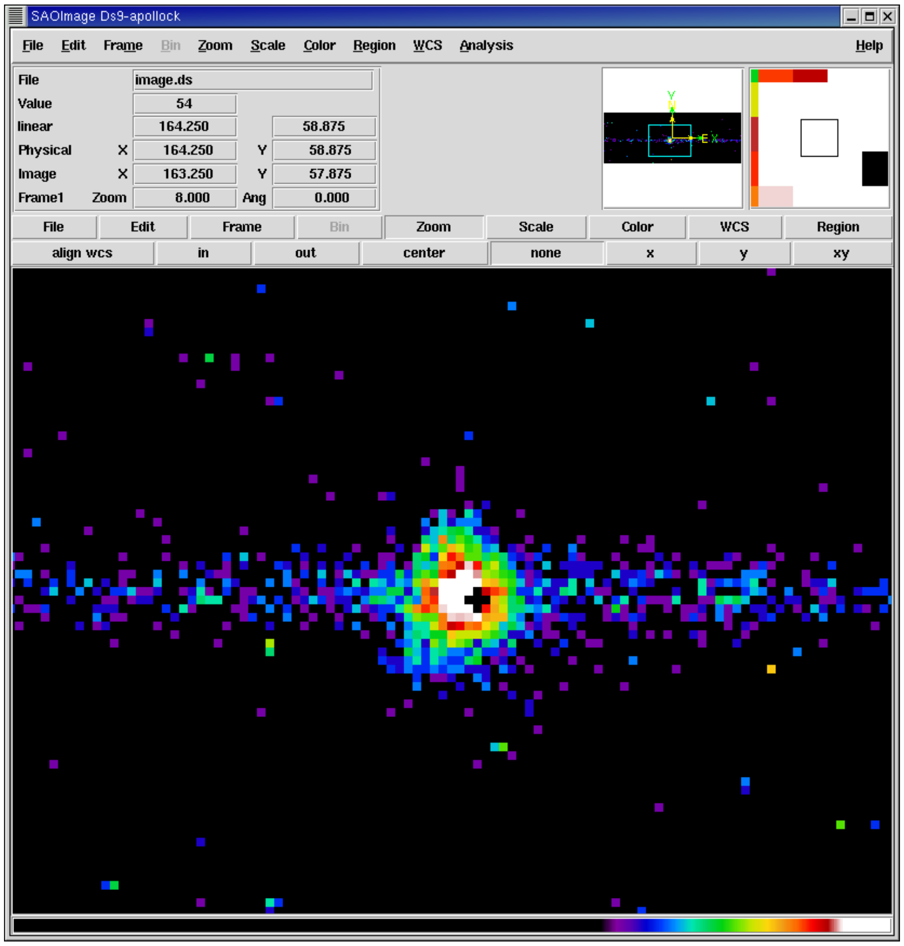
`http://www.cosmos.esa.int/web/xmm-newton/calibration-documentation`

5.12 Creating RGS response matrices

As emphasised above, the source coordinates are most crucially under the observer's control and have a profound influence on the accuracy of the wavelength scale as recorded in the RGS response matrix, or RMF, that is produced automatically by `rgsproc` using the task `rgsrmfgen`. There are different RMFs for RGS1 and RGS2 and for each order. Many parts of the instrument model held in the CCF are also used to describe the geometry and radiation transfer properties of each component of the instrument from telescope, through grating assembly to detector and these are not normally subject to change. An RMF is used to connect an input wavelength or energy grid representing cosmic physical units to the output instrumental channels in which the observed selected data have been cast. While the spacing of the output grid is fixed by a requirement to sample sufficiently the instrumental resolution and must agree with the relevant accumulated spectrum, the input grid is another quantity under the user's express control via the `rgsrmfgen` parameters `emin`, `emax` and `rows`. Although wavelength units are natural for grating spectrometers, the OGIP RMF standard requires energy units, given here in keV. Here is an example of an independent run of `rgsrmfgen` from the command line to generate the 2nd order RGS2 matrix for Mkn421:

```
 rgsrmfgen spectrumset=P0136540101R2S002SRSPEC2003.FIT \
           evlist=P0136540101R2S002EVENLI0000.FIT \
           emin=0.4 emax=2.5 rows=5000 rmfset=RGS2.o2.rmf
```

Despite the elongated appearance of spectral lines in plots like Fig. 45, the point-source monochromatic response is in fact reasonably symmetric as shown in Fig. 47. Although a typical line covers several pixels, it is possible to locate line centroids to a fraction of a pixel. In this case, it is necessary to generate response matrices with a much more dense grid than usual in order to take full advantage of all the information available in the data and calculate reliable errors. RGS calibration work in the past has used 1st-order matrices with between 20,000 and 50,000 rows but there are drawbacks. The files are very big and some third-party tools are unable to cope with them.


SAOImage Ds9-apollock
File Edit Frame Bin Zoom Scale Color Region WCS Analysis Help
File Edit Frame Bin Zoom Scale Color WCS Region
align wcs in out center none x y xy

File		image.ds		
Value		54		
linear		164.250		58.875
Physical	X	164.250	Y	58.875
Image	X	163.250	Y	57.875
Frame1	Zoom	8.000	Ang	0.000

Figure 47: A bright OVIII emission line in raw detector coordinates showing the reasonably circular symmetry of the RGS's monochromatic response. A hot pixel has been detected near the core causing it to be masked out with its immediate neighbours when the default rejection flags are applied.

5.13 Heliocentric velocity correction

Due to the motions of the Earth around the Sun and the spacecraft around the Earth, the observed wavelength of a line emitted by a celestial object is affected by the Doppler effect induced by the spacecraft velocity component in the direction of the target. Spectral lines measured from a high-resolution spectroscopy instrument, such as RGS, must then be corrected for the projected component of the satellite's velocity. The task `rgsproc` can be instructed with the switch `withheliocorr` to apply this correction and report the value in the `VHELIOCOR` keyword in the header of the spectrum. Starting in SAS v14.0, this correction is applied by default.

5.14 Sun Angle correction to the wavelength scale

Studies of RGS spectra of emission line sources have shown that line positions are systematically shifted with respect to laboratory wavelengths, and that the wavelength scales of both RGS are displaced by a few mÅ. A strong correlation has been found between the line shifts and the angular distance between the spacecraft pointing direction and the Sun (see `http://xmmweb.esac.esa.int/docs/documents/CAL-SRN-0297-1-0.pdf`). A correction for this effect has been implemented for the first time in SAS v13.0, through the `rgsproc` parameter `withsunaglecorr`. Starting in SAS v14.0, this correction is applied by default.

5.15 Combination of RGS spectra

The task `rgscombine` can be used to combine two or more spectra that have been produced by `rgsproc` for the same order into a single spectrum and to calculate the corresponding combined response matrix. In order for the task to run, the component spectra must have been calculated by `rgsproc` on a fixed wavelength grid (the `rgsproc` default). This method maintains proper counting statistics and has replaced earlier techniques. Refer to the SAS web pages section on individual tasks for more information,

`http://xmm-tools.cosmos.esa.int/external/sas/current/doc/rgscombine`

Users are warned to examine the output of this task carefully, as the algorithm is very sensitive to small pointing differences. Also, results can be problematic when combining spectra with different intensities.

5.16 RGS small-window mode

From SAS v11.0, RGS Small Window mode exposures are processed automatically. In this , designed to reduce pile-up in bright sources, only central parts of the CCD detectors are read out. As background spectra are normally calculated from data at the edges of the detectors, none are available in this mode.

5.17 Use of `rgslccorr`

By default, `rgsproc` calculates a single spectrum per RGS per order per observation even though variability is a common property of many X-ray sources. The task `rgslccorr` allows users to produce background-subtracted and exposure-corrected RGS light curves from the same spectral and background selection regions that are used to generate spectra. It is possible to generate light curves without background subtraction through the use of the parameter `withbkgsubtraction`. `rgsproc` uses event and source-list files to calculate background and dead-time corrections to produce light curves defined by parameters such as time bin size, start and stop time, and spectral order. Combined light curves are possible of simultaneous RGS1 and RGS2 data.

Fig. 48 shows a comparison of RGS light curves versus the corresponding EPIC-pn light curve.

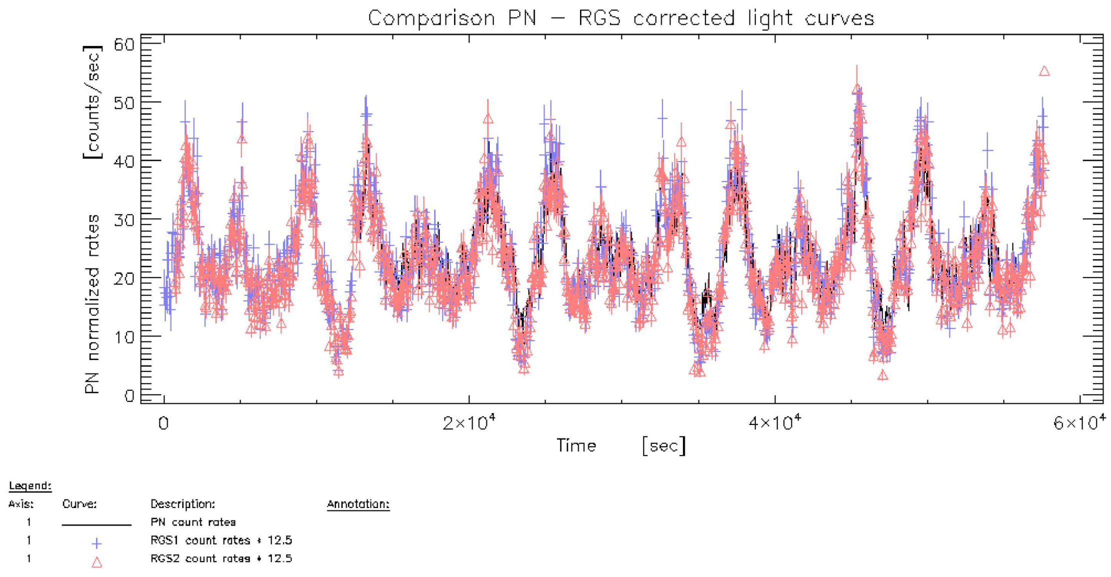


Figure 48: Comparison of RGS and PN light curves.

5.18 Use of rgsfluxer

Although a rigorous analysis of RGS spectra for calculating physical model parameters requires the simultaneous use of individual spectra and their associated response matrices, it is often useful to produce a figure to show the overall properties of an X-ray spectrum observed with the RGS. The task `rgsfluxer` can be used to produce a single illustrative fluxed spectrum from any number of component spectra and response matrices from any combination of RGS1 and RGS2 and 1st and 2nd order. In contrast with `rgscombine` described in § 5.15, the spectra do not need to be aligned. If the spectra are not background corrected, which is the default for `rgsproc`, don't forget to tell `rgsfluxer` about the background spectra. For example, if several total and background spectra of HR1099 are collected in a directory, the following commands will produce the rough picture of the mean stellar spectrum shown in Fig. 49.

```
setenv SPECTRA *SRSPEC*
setenv BKGs    *BGSPEC*
setenv RMFs    *RSPMAT*
rgsfluxer pha="$SPECTRA" bkg="$BKGs" rmf="RMFs" file=HR1099.RGS.spectrum
```

The output of `rgsfluxer` is a tabulation of physical flux against wavelength and it can be useful for this to serve as an model-free input spectrum for comparison with lower-resolution spectra from the EPIC instruments, for example, in particular. The task `rgsfluxmodel` recasts the output of `rgsfluxer` into a file format suitable for use as an `Xspec` table model that can be read into `Xspec` using the `atable` command.

5.19 The RGS pipeline products

The PPS products generated by rgsprods, an automatic version of `rgsproc`

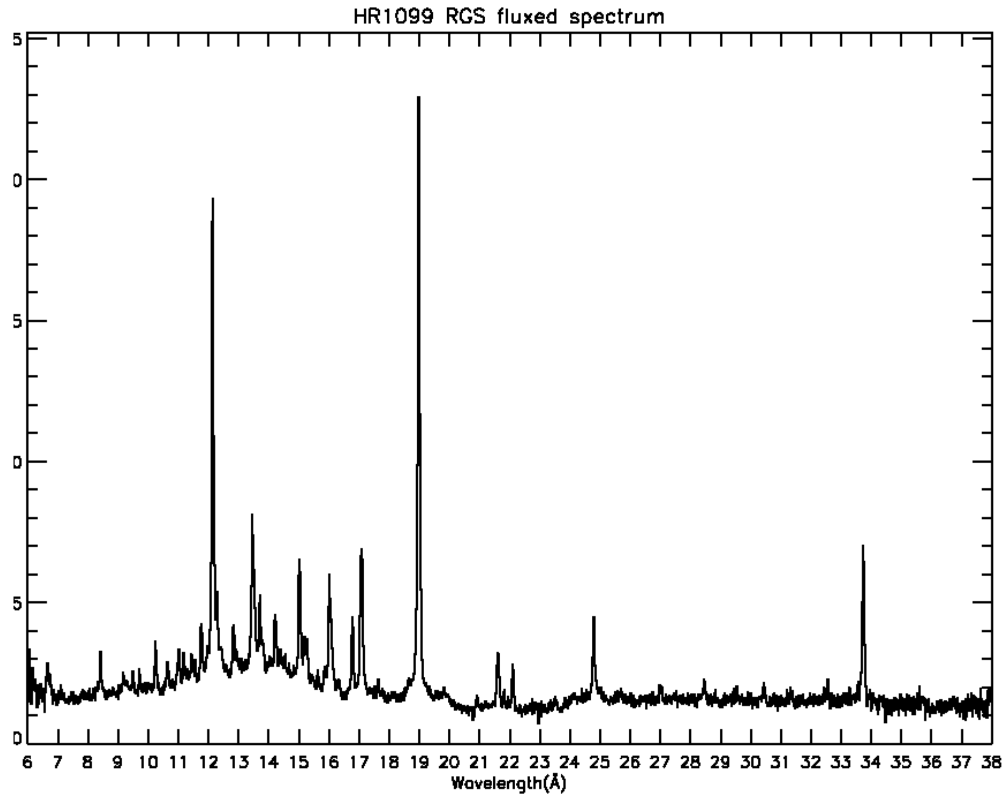


Figure 49: The fluxed spectrum of HR1099 produced with `rgsfluxer` made from a combination of 86 1st and 2nd order RGS1 and RGS2 spectra.

`http://xmm-tools.cosmos.esa.int/external/sas/current/doc/rgsprods`

have some differences compared to the files produced interactively. The number of RGS pipeline products is quite large (see the Pipeline Products Description document) but may be handled with ease by pointing a browser to the hypertext index files, starting with **INDEX.HTM**, included in the distribution. RGS pipeline product file names are of the form :

- PiiiiiijjkkaablllCCCCCCmnnn.zzz, where

  iiiiiijjkk observation number

  aa detector, R1 - RGS1, R2 - RGS2, RG - both

  b S for scheduled observation, U for unscheduled, X for general purpose

  lll exposure number or 000 if none

  CCCCCC file identification shown in Table 9

  m order number

  nnn source number

  zzz file type

  FTZ gzipped FITS format for use, for example, with `xmmselect`, `ds9` or `fv`

  HTM HTML file for use web browser

PDF Portable Document Format file
PNG Portable Networks Graphics file
TAR TAR file

File ID	Contents	File Type
PPSSUM	PPS summary	HTML
OBX000SUMMAR	Observation Data File Summary	HTML
SUMMAR	RGS Processing Summary	HTML
FLUXED	Combined RGS1 & RGS2 1st order fluxed spectrum	FTZ & PDF
BGMODL1	synthetic 1st order background spectrum	FTZ
BGMODL2	synthetic 2nd order background spectrum	FTZ
BGSPEC1	1st order background spectrum	FTZ
BGSPEC2	2nd order background spectrum	FTZ
DSPHIS1	cross-dispersion histogram	FTZ
EVENLI	combined events list	FTZ
EXPMAP	exposure map	FTZ
FBKTSR	background light curve	FTZ
IMAGE_	χ vs β spatial image	FTZ & PNG
ORDIMG	PI vs β banana plot	FTZ & PNG
RSPMAT1	1st order response matrix	FTZ
RSPMAT2	2nd order response matrix	FTZ
SBSPEC1	1st order source total spectrum	FTZ
SBSPEC2	2nd order source total spectrum	FTZ
SRBTSR	background timeseries	FTZ
SRCLI_	source parameters	FTZ
SRCTSR	background-subtracted source timeseries	FTZ
SRSPEC0	1st & 2nd order source net spectrum plot	PDF
SRSPEC1	1st order source net spectrum	FTZ
SRSPEC2	2nd order source net spectrum	FTZ
WFSPEC0	1st & 2nd order whole-field total spectrum plot	PDF
WFSPEC1	1st order whole-field total spectrum	FTZ
WFSPEC2	2nd order whole-field total spectrum	FTZ
WREMAT1	1st order whole-field response matrix	FTZ
WREMAT2	2nd order whole-field response matrix	FTZ

Table 9: Pipeline Processing data files relevant for RGS.

6 Analysis of OM optical monitor data

6.1 The OM data

6.1.1 OM observing modes and data types

The OM can be operated in two basic science modes: image and fast mode (see the OM dedicated section of the UHB for further details). These modes can be used separately or combined, in different instrument configurations:

- Default modes: Image_only and Image+Fast. This is a set of 5 successive exposures with predefined windows configurations covering nearly 92% of the field with/without a Fast mode window centered at the boresight location.
- Science User Defined Image and/or Fast mode windows: the user can define in pixels or in (RA, Dec) up to 5 windows, from which up to 2 can be defined in Fast mode
- In addition, the OM detector can be operated in Full Frame mode to obtain images of the entire FOV, either at high resolution (0.5 arcsec/pix, 2048×2048 format) or at low resolution (1 arcsec/pix, 1024×1024 format).

In the windowed modes, the detector windows are re-centered to correct for pointing errors (Field Acquisition, FAQ). Also a shift_and_add mechanism is used to compensate for spacecraft tracking stability. Full frame modes do not have these capabilities.

The observing modes determine the type of data obtained with the OM: 2-D images for image modes and events lists if fast mode is used.

The default modes mentioned above will produce the following data types: since each exposure has two image windows associated with it, there will be two image files per exposure which correspond to a small high resolution window at the centre of the FOV and a large low resolution one placed at different locations in each exposure. If the default mode was Image+Fast, there will be an additional event list file corresponding to the Fast window.

In the Science User Defined windows configuration there will be one image file or event list corresponding to each of the windows.

The Full Frame images consist of a single image file if high resolution was used and four adjacent image files in case of low resolution. (It should be noted that the four image files correspond to a unique exposure).

In addition to these image and/or event list files, for each exposure, there will be several auxiliary files containing instrument configuration parameters. There will also be files containing OM house-keeping data for the whole observation. All these files together with the spacecraft attitude and time correlation files, common for all instruments, constitute the ODF for OM data.

Table 10 contains a summary of the possible OM files contained in an ODF (for one exposure).

OM Images files have a file name ending in ”IMI.FIT”. There is one image file per image mode window per exposure. Raw image files can be displayed with e.g. the `ds9` image viewer. It is also possible to combine all processed image windows of an OM default configuration before viewing them using the SAS task `ommosaic`.

Data Identifier	Contents
00IMI	Image window 1
01IMI	Image window 2
FAE	Event list (if fast mode was used)
THX	Tracking history
WDX	Priority window data
PFX	Priority fast mode data
RFX	Priority reference frame data
PAX	Field acquisition data
PEH	Periodic house-keeping
NPH	Non-periodic house-keeping
E4I	Full frame high resolution image

Table 10: ODF data file identifiers associated with a single OM exposure.

OM full frame high resolution images have a name ending in "E4I". Full frame low resolution follow the general nnIMI rule, with nn=00,01,02,03 (four files per exposure).

OM Fast mode event lists have a file name ending in "FAE.FIT". There is one dataset for each fast window. It is possible to inspect the data files using e.g. the ftool viewer `fv`.

OM reference frame data have a file name ending in "RFX.FIT". Generally one file is present for each exposure, except if tracking was switched off. This is the case for certain OM engineering modes and certain filter elements (e.g. grism).

OM tracking history file data have a file name ending in "THX.FIT". Generally one file is present for each exposure, except when tracking was explicitly switched off, or when no suitable stars for tracking were found in the reference frame at the beginning of the exposure. It is possible to inspect these files with e.g. the ftool viewer `fv`. A plot of column DX and DY shows the attitude stability during the exposure. The PPS product file whose name ends in "TSHPLT.PDF" provides a visualisation of the pointing stability during the exposure in PDF format.

OM field acquisition data have a file name ending in "PAX.FIT". There is only one field acquisition dataset present per observation. In order to get a feeling on the absolute pointing accuracy, the user can look at this field acquisition dataset (PAX.FIT). The parameters DX, DY provide the absolute pointing error in units of 0.001 subpixel.

OM priority window data have a file name ending in "WDX.FIT". One priority window dataset is present for each exposure. This file is used, e.g. to compute the exposure dead-time fraction.

OM priority fast mode data have a file name ending in "PFX.FIT". There is one dataset for each exposure containing fast mode window(s).

6.1.2 OM: filters and grisms

Before reaching the detector, photons collected by OM are intercepted by one of the elements of the Filter Wheel. These are six wide-band filters, called (in increasing wavelength order) UVW2, UVM2, UVW1, U, B and V. Another filter, called White covers the full spectral band from UVW2 up to V (1800 Å to 6000 Å approximately). There is a Blocked (opaque) filter used in some engineering modes and also to protect the OM when there is a too bright object in the field of view. All these filters can be used in both observing modes, image and/or fast mode, with all the configurations described in section § 6.1.1.

The filter wheel has in addition two grisms, Grism1 or UV grism and Grism2 or Visible grism, which can be used to obtain low resolution spectra in the range 1800 to 3600 Å and 3000 to 6000 Å, respectively. Both grisms are used only in image mode. There is a user-defined default configuration intended for single object spectroscopy, in which a rectangular window is defined so that it contains the spectrum of the target sitting at the boresight. Alternatively, the grisms can be used in full frame low resolution to register the spectra of all objects in the field of view. Data obtained with the grisms are therefore image data with the same characteristics as defined above.

It should be noted that in early phases of the project some observations with the OM grisms were done using the image default configuration described above (§ 6.1.1). These few cases cannot be dealt with by the SAS. Even if grism data can be considered as normal image data, only the observations obtained as single object spectroscopy or in full frame as explained before, can be processed by SAS.

6.1.3 Listing the OM Current Calibration Files

Table 11 provides a list of the OM calibration files. For a detailed description of these files and of their usage, the user is referred to the CCF Interface Control Document [5] (see § 1.2). Some of these files are only used by the real time PHS and QLA systems, although they are contained in the SAS file *ccf.cif*. The SAS tasks using a given CCF are indicated as well.

6.2 Description of the OM image data processing chain `omichain`

The processing of OM data with SAS is run by the pipeline at the SOC. Users can also process their data at their home institute using SAS. Three processing chains, `omichain`, `omfchain` and `omgchain` are used for image, fast mode data and grisms spectra processing, respectively. The chains are Perl scripts that concatenate the individual SAS tasks so as to go from the input raw data up to the final output results without further interaction. The tasks can also be run one by one having more control on all needed parameters.

In the following pages we describe this processing paying attention to the concepts and functions implemented in the different tasks to accomplish all corrections and calibrations necessary to exploit OM data. A detailed description of the tasks and the parameters controlling their functionality is provided in the SAS on-line documentation and processing threads.

It should be noted that the pipeline does not run the processing chains we describe, but an equivalent concatenation of the same SAS tasks.

The whole processing of image and fast mode data is depicted in figure 50 and figure 51. Figure 52 gives an overview of the reduction of spectral data.

In order to process the OM image data successfully, an input dataset is required. Input datasets are not changed during the OM processing with `omichain`. They are copied to intermediate datasets and keywords. Extensions are added to the FITS data files as needed. Intermediate task products, which are passed from one task to another, are generally not described.

The processing of OM image data can be divided in three parts (see figure 50),

- **Data preparation.** Before real processing, if present, the four files composing a full frame low resolution exposure are combined into a single one using `omcomb`. Also a flat-field for later usage is obtained with `omflatgen`.
- **Image processing.** All corrections, source detection, astrometry and photometry are applied to each image file, exposure by exposure. `omichain` will process, automatically, all image data consecutively. However, the user can process single image files by applying the different tasks one by one in a semi-interactive way.

  This core of the image processing can be divided as well,

  - **Preparation of tracking corrections**
  - **Corrections: bad pixels, fixed pattern, flat-field**
  - **Source detection, astrometry and photometry**
- **Combined results.** The source lists corresponding to different exposures, using different filters, are combined with `omsrclistcomb`. Colour indices are also calculated. The images corresponding to different windows observed with the same filter are mosaiced (or stacked) in a single image file using `ommosaic`. Mosaiced images may be source-searched for fainter sources and the results merged into the combined source list.

As can be seen in the flow chart of the OM processing chain (figure 50), the OM tracking information for each exposure is treated before, and independently from, the image data processing. In the following, for each task description, a reference is given to the analysis step in the processing example.

6.2.1 Data preparation

- `omcomb` is used before real processing, to combine the four files composing a full frame low resolution exposure into a single one which will be the subsequent input for the process.
- `omflatgen` generates the flatfield file for the observation. The flatfield file is distributed as a PPS product (FLAFLD). In absence of a FLAFLD.FIT file in the PPS products, a dummy file can be generated by the task `omflatgen`. In this case the flatfield response is set to unity.

It should be noted that the characteristics of the OM detector imply that flat field correction has to be treated in a different way than in a normal CCD.

The physical pixels are subsampled by the centroiding algorithm, thus the concept of pixel to pixel variations changes since the real pixel cannot be recovered. A fixed pattern appears instead and it is corrected at a later stage in the processing.

It has been shown by studying the accuracy of the OM photometric calibration, which is based on observations of a large number of stars with OM and from the ground, and the statistical

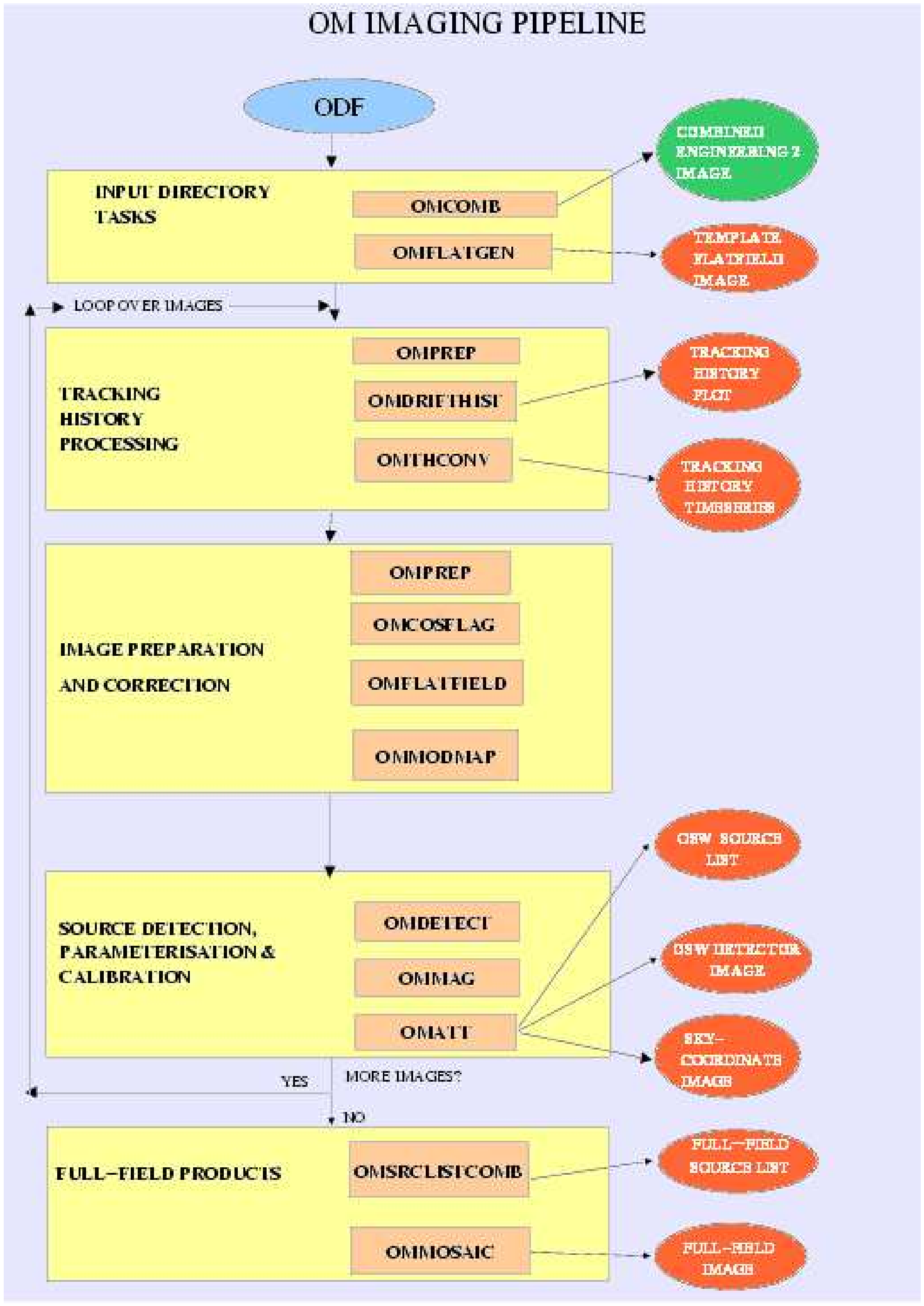


Figure 50: SAS processing chain for data acquired in the OM imaging mode.

errors of the measurements, that the results obtained with OM are accurate to within a few percent without flat field correction. Furthermore, observations of the same stars in different parts of the detector show that large scale sensitivity variations are smaller than two per cent. Therefore, the SAS uses a unity flat field file for processing OM data.

6.2.2 Handling of tracking data

Two output datasets related to tracking data are distributed as pipeline products, namely the TSHPLT.PDF and the TSTRT.FIT file. They are created as follows.

- `omprep` (step1). The task `omprep` does not generate final data products but only intermediate files. OM images, tracking history files and fast mode files if any, are copied into temporary files. Further information is added via keywords. Intermediate products are generated, which carry information extracted from the tracking history file. If no tracking history file was produced, these are generated on the fly assuming perfect stable pointing. Tracking history data can be missing if no suitable tracking stars were available during the observation. This can also occur when certain instrument modes (full frame, engineering modes) or when some filter elements (e.g. grisms) are used.
- `omdrifthist` (step2). This task creates the TSHPLT.ps file (TSHPLT.PDF in the pipeline processing), which provides an overview of the pointing stability during an exposure. The file contains diagrams illustrating the absolute and incremental OM drift.
- `omthconv` (step3). This task creates the TSTRTS.FIT file, which contains the tracking star time series, i.e the average count rate (cts/s) per tracking frame for each tracking star.

6.2.3 Handling of corrections applied to image mode data

As pointed out before, an observation with OM may be composed of several exposures which contain different observed windows. There are three final data products per observed science window (OSW), namely IMAGE_.FIT, SIMAGE.FIT and SWSRLI.FIT. Two additional products, FLAFLD.FIT and OBSMLI.FIT, are generated on a per observation basis. The task `omichain` loops over all image mode data files of all exposures in an observation.

The following tasks are applied to each individual observation window.

- `omprep` (step4). The task `omprep` copies the raw images into an intermediate output file. It adds several keywords to this intermediate output file. Although this file is not a final data product, it is carried forward within the processing of OM image data and ends up being contained in the final IMAGE_ product.
- `omcosflag` (step5). The task `omcosflag` generates a quality map. Bad pixels are flagged taking also into account the tracking history information. The quality array (bad pixels are flagged as non-zero there) itself is written into the quality extension of the intermediate image files. It is used later by other tasks and it is propagated into the IMAGE_.FIT PPS output file.
- `omflatfield` (step6). The task `omflatfield` applies the tracking history file (as contained in the intermediate processing product of the tracking history task) to the OM flatfield file (FLAFLD). The resulting drift corrected flatfield file is applied to the intermediate OM image file. The flatfield corrected OM image is written as

an intermediate data product, which is used as an input to `ommodmap`. Since the current flat field is unity, this correction has no effect on the data.

- `ommodmap` (step7). The task `ommodmap` applies the modulo 8 correction to an OM image. The modulo 8 background fluctuations are introduced to an OM image by imperfections of the photon centroiding algorithm. An intermediate image file is generated, which acts as input to the task `omdetect`.

6.2.4 Source detection, astrometry and photometry

- `omqualitymap` (step8). With this task image quality information is stored for later use. Pixel quality information is carried on and assigned to detected sources through quality flags. It will be used for additional source detection in mosaiced or stacked images.

- `omdetect` (step9). The task `omdetect` applies a source detection algorithm to find the sources present in the image. First the background is modelled. Then the algorithm looks for sources matching the criteria defined by the task parameters. Aperture photometry is applied to the detected sources. The point spread function (PSF) of OM is taken into account. The output is a source list (SWSRLI) which contains the source positions in absolute detector pixel and the calculated sources and background count rates (cts/sec). Coincidence loss correction is also applied to the count rates of the sources and the background. An optional output file, called the region file, can be generated with a name defined by the parameter `regionfile`. The region file describes the area associated with each identified source in the image. It is used by the image display tool.

  Extended sources are also identified if the parameter `detectextended` is set. The photometry of an extended source is made by adding all the counts received in an elliptical area and the background is measured in an annulus, as for point sources. Coincidence loss correction is applied by considering that every pixel is a point like source.

  Since SAS v9.0, `omdetect` can be used on final mosaiced or stacked images in order to find fainter, previously undetected sources.

- `omqualitymap` (step10). In this second call the task uses the stored pixel quality information to assign quality flags to the previously detected sources.

- `ommag` (step11). The task `ommag` converts count rates into the instrumental OM photometric system. Count rates are corrected for detector deadtime. Time sensitivity degradation of the detector is computed for the epoch of the observation and the count rates are corrected for this effect. For the UV filters, the PSF is extrapolated to account for the larger aperture of 35 pixels radius. The corrected count rates are converted into instrumental magnitudes. The task requires input from the source list file SWSRLI. The output is added as extra column to the source list file (SWSRLI). The sensitivity limit of the specific exposure and the time sensitivity degradation are written as keywords in the source list.

- `omatt` (step12). The task `omatt` reads the intermediate image generated by `ommodmap` and reads the source list file generated by `omdetect` and `ommag`. It converts detector position from pixel coordinates into RA/Dec positions based on information from the attitude history file, the instrument boresight file and the OM filter distortion map. Since SAS 12, the attitude is obtained by default from the so-called Raw Attitude File (*RAS.ASC) instead of the Attitude History File (*ATS.FIT). This new method provides a better attitude reconstruction. The celestial positions are added as two new columns to the SWSRLI.FIT file. A subset of USNO catalogue can be provided optionally. Then source cross correlation will be performed and the computed offsets will be added to the derived coordinates of the sources. The most accurate astrometry can be achieved in this way. If the catalogue file is not present, then `omichain` will attemp to run `scat` to produce the catalogue file. This requires that this utility is installed into the system, otherwise source cross correlation will not be performed.

A skyimage (SIMAGE.FIT) is generated from the input image, by resampling the image, applying the distortion correction and north aligning the image. No other correction is applied to this image, i.e. coincidence losses and deadtime are not corrected. The skyimage provides the most accurate positional information of an image in the OM image data processing chain. Note that IMAGE_ has no distortion correction and therefore its positional information is less accurate than in the SIMAGE.

6.2.5 Final combined results

- `ommosaic` (step 13). In case of multiple OM exposures of the same field, with the same filter, `ommosaic` is used to combine the corresponding skyimages into a single skyimage. If this task is used for the default image mode, it will combine the windows of the five exposures obtained with the same OM filter into a full field image. Otherwise, skyimages are stacked together. Note that the final image is not corrected for coincidence losses nor for deadtime. The exposure times of the original images composing the mosaic are normalised to 1000 seconds.

- `omsrclistcomb` (step14). The source lists of the different OSW's of all exposures contained in an observation are combined into one single observation source list file using `omsrclistcomb`, which is invoked when the analysis of the individual science windows is finished. The input parameter `nsigma` defines the criteria for the spatial matching of two sources in the merging of the source lists. `omsrclistcomb` generates a master source list with RA/Dec coordinates, RA/Dec errors and galactic coordinates. The list is sorted into increasing RA order. The significance of detection, the instrumental magnitude and its error, the semi-axis of the source detection ellipse and a set of flags are written in the source list for each filter used in the observation. The colour transformations are applied and the source brightness is also listed in a standard photometric system. AB magnitudes and absolute fluxes are also computed and included in the combined source list.

  As in `omatt` (step 12) if a catalogue file is provided, then the merged list sources are again cross correlated. This allows to derive a correction for sources detected in the UV filters, which in fields with low number of sources detected fails in the first cross correlation done with `omatt`.

6.2.6 Source variability: `omvariability`

- `omvariability` (step15). If an observation contains several exposures obtained with the same filter, the task `omvariability` reads the source lists of all exposures within the observation and looks for variability of all detected sources. A chi square test is run to assess possible variability. The results are added to the combined source list, and light curves are plotted for the sources considered as variable. See the SAS on-line documentation for further details.

6.2.7 Deep detection on mosaiced images

Since SAS v9.0 it is possible to run `omdetect` on mosaiced images. Invoking `omichain` with the parameter `processmosaicedimages` will produce a second detection on mosaiced images (if any). New detected sources will be added to the source list. This is the default in SAS v13.0.

- `omdetect` (step16). A second detection is done in the mosaiced and stacked images (if any). This produces a new source list.
- `ommag` (step17). Calibration is applied to the sources of the new list.
- `omqualitymap` (step18). Quality flags are set for the sources.
- `omsrclistcomb` (step19). The sources obtained from the mosaiced and stacked images are merged as in step14.
- `ommergelists` (step20). The new sources detected in the mosaiced and stacked images are added to the original combined list. Existing sources from the first run of `omdetect` in the original images are not changed.

This deeper detection can be applied manually to co-added or mosaiced images from different observations. Since these new sources are very faint the coincidence loss correction is not applied to them. (See the SAS on-line documentation for further details)

It should be noted that this second detection is performed on sky aligned images. Errors in the alignement of the rotated images and rotation induced noise patterns can lead to spurious detections. All new sources are flagged in the final merged list produced by `ommergelists`.

6.2.8 Further notes on processing of OM image data

With the default settings, `omichain` overwrites temporary files at several stages, e.g when looping over multiple exposures or even within the analysis of a single window. This can be avoided by specifying unique output file names. It is recommended to clear out (removing or renaming) products of previous `omichain` runs before re-invoking `omichain`.

6.2.9 Interactive source detection and photometry

The task, `omphotom`, is intended for interactive photometry. It does not have a graphical user interface, but it runs from the command line.

omphotom allows the user to recompute the photometry of one or several sources in a list previously obtained with omichain. The aperture and background regions definition can be modified. For crowded fields, a least squares fit to the PSF can be done. This can give better results than the standard mode used in omichain.

The task can accept as input a parameter file that allows specifying several input images and the corresponding source files. This allows batch processing of many exposures in the same observation.

Potential users are referred to the on-line documentation for omphotom.

6.3 Description of the OM fast mode data processing chain omfchain

As we did for image data, we describe now the functionality of the fast mode data processing. For a detailed description of the tasks and the parameters controlling them we refer the User to the SAS on-line documentation and processing threads.

The example input dataset given in Table 10 contains also fast mode data files. To process them with SAS, the task omfchain has to be used. As for image data, the input data do not change through the fast mode chain.

The process is similar to the one for image data. It can be followed in figure 51. For each fast mode window of the different exposures in the observation (ODF) there will be

- **Data preparation: tracking correction.** The tracking data, which are common for image and fast mode data, are treated to derive the corrections to be applied to the events detected in an exposure.
- **Event selection and corrections.** The event list file is scanned to find the photon events. Then tracking and flat field corrections are applied.
- **Source detection and astrometry.** The source is located within the fast mode window (eventually more than one source) and astrometry conversions are applied.
- **Light curve.** Count rates are derived for the source(s) and the background. Then a light curve is produced giving the net countrate as a function of time for each source found in the fast window in each exposure. A graphical output is produced as well.

6.3.1 Data preparation: tracking correction

The same tasks used in the image chain are repeated here:

- omprep (step1). The task omprep does not generate final data products but only intermediate files. OM images, tracking history files and fast mode files if any, are copied into temporary files. Further information is added via keywords. Intermediate products are generated, which carry information extracted from the tracking history file. If no tracking history file was produced, these are generated on the fly assuming perfect stable pointing. Tracking history data can be missing if no suitable

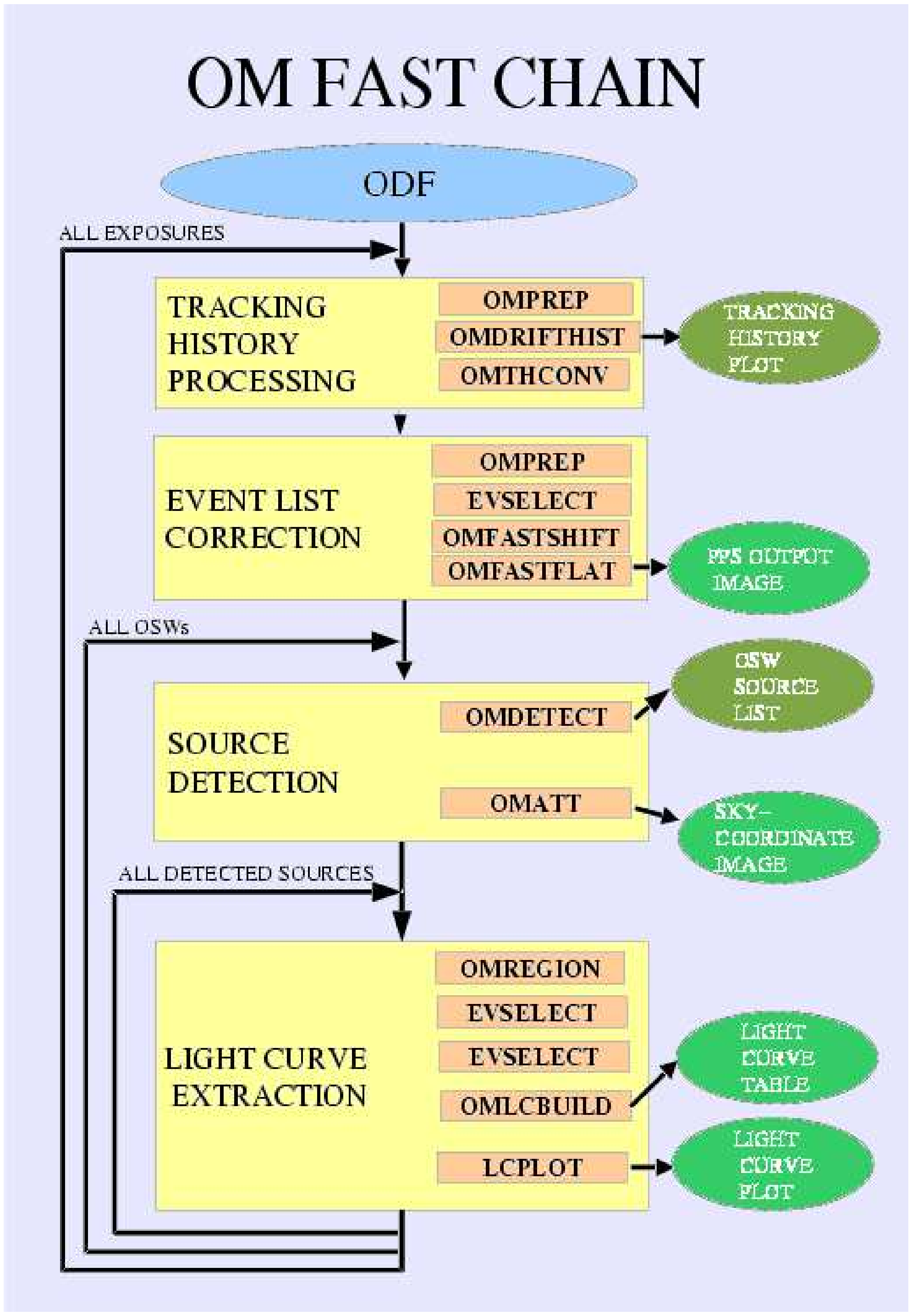


Figure 51: SAS processing chain for data acquired in the OM fast mode.

tracking stars were available during observation. This occurs frequently when UV filters are used.

- `omdrifthist` (step2). This task creates the TSHPLT.ps file (TSHPLT.PDF in the pipeline processing), which provides an overview of the pointing stability during an exposure. The file contains diagrams illustrating the absolute and incremental OM drift.

- `omthconv` (step3). This task creates the TSTRTS.FIT file, which contains the tracking star time series, i.e the average count rate (cts/s) per tracking frame for each tracking star.

6.3.2 Event selection & corrections

The following tasks are applied to each individual fast mode window,

- `omprep` (step4). The task `omprep` applied to the event list file will augment its header contents with house-keeping information. A modified intermediate event list file will be created.
- `evselect` (step5). The task `evselect` extracts the photon events from the event-list file and builds a pseudo image corresponding to the fast mode window.
- `omfastshift` (step6). The task `omfastshift` uses the tracking history file (as contained in the intermediate processing product of the tracking history task) to correct the position of the photon events for drifts of the spacecraft during the exposure. New columns are added to the event-list file with corrected coordinates.
- `omfastflat` (step7). The task `omfastflat` applies the tracking history file to the OM flatfield file (obtained from `omflatgen`) to build a shifted flat field corresponding to the fast mode pseudo image.

  It is pointed out again the peculiarity of the flat field for OM. As for image data, a unity flat field is applied to fast mode data as well.

6.3.3 Source detection & astrometry

- `omdetect` (step8). The task `omdetect` applies the source detection algorithm to the fast mode pseudo image to locate the existing sources. It builds a source list similar to the image data one (SWSRLI) which contains the source position in absolute detector pixel and the calculated source and background count rates (cts/s).
- `omatt` (step9). The task `omatt` performs astrometry conversions from pixel positions to astronomical coordinates in the source list and rotates the pseudo image to obtain a north aligned skyimage.
- `omregion` (step10). The task `omregion` produces the regions for the source and background needed later for `evselect`
- `evselect` (step11-12). The task `evselect` is run twice consecutively on the event-list file to extract the photon events for the source and the background in the specified time sampling. Intermediate rate files are created for the source and the background.
- `omlcbuild` (step13). The task `omlcbuild` generates coincidence loss and dead-time corrected source time series using the source and background rates produced by

`evselect`. The background rates are subtracted and the photometry corrections are applied. If the source is offset from the centre, the knowledge of the PSF is used to account for possible missing photons. Time dependent sensitivity degradation is corrected as for image data. A light-curve is obtained as final result for each of the sources in the fast mode windows in the exposure.

The parameter `bkgfromimage=yes` can be used to measure the background in the associated image mode data. This is the default option in SAS version 14. (See section § 6.3.4.)

- `lcplot` (step14). The task `lcplot` reads the light-curve file and makes some plots. Some statistics are also applied to assess possible source variability.

6.3.4 Measuring the background from image data

Normally, in all cases when OM fast mode is used, the small fast window is embedded into a larger image mode window. If the target in the fast window is moderately bright, or if more than one source are present in the fast window, it is advisable to obtain the background from the image data. Using the parameter `bkgfromimage=yes` within `omfchain` will produce a constant background extracted from the corresponding image data for the whole exposure that will be subtracted from the source fast mode count rate. This is the default option in `omfchain` since SAS 12.

6.4 Description of the OM grism data processing chain `omgchain`

The processing of grism data is very similar to the one performed in image data by `omichain`. Some tasks used there are also applied to grism data. The whole process is shown in figure 52. It can be divided into:

- **Data preparation.**

  For data obtained in full frame (field spectroscopy), the four files composing a full frame low resolution exposure are combined into a single one using `omcomb`.

- **Image processing.**

  As in all OM image mode data, `omprep` is run to extract information from the tracking history and house-keeping files and to add it to the header. `ommodmap` performs a modulo_8 correction on the grism image to eliminate this fixed pattern noise.

  Then the grism image is corrected from geometric distortion of the detector and then it is rotated so as to have the dispersion direction (the spectra) aligned with the image Y axis. The task `omgprep` is used to achieve this.

- **Source detection, astrometry, spectral extraction and calibration**

  `omdetect` is used also in grism data to search the image for spectra, both zero and first orders. A source list is generated with all successful detections.

  As with normal image mode data, `omatt` is used to compute the astronomical coordinates of the sources producing the extracted spectra. A sky aligned grism image is also produced.

Then, `omgrism` will analyse the detections in the source list to establish relations between detected zero orders and the corresponding first orders. A boxcar extraction is performed on the successful relations. The extracted spectra are calibrated in wavelength and flux. In case a relation cannot be found for well defined zero orders, a default extraction is used for the corresponding zero order. The final spectra are written into a fits file.

Finally, `omgrismplot` is used to produce plots of the spectra (net spectrum, background and flux calibrated) in PDF and PS formats.

The complete processing chain extracts by default only the spectrum of the main target, or object placed at the XMM-Newton boresight, and this is what the user will find in the final products. Alternatively, the user may select to extract all objects in the field of view (`extractfieldspectra=yes`).

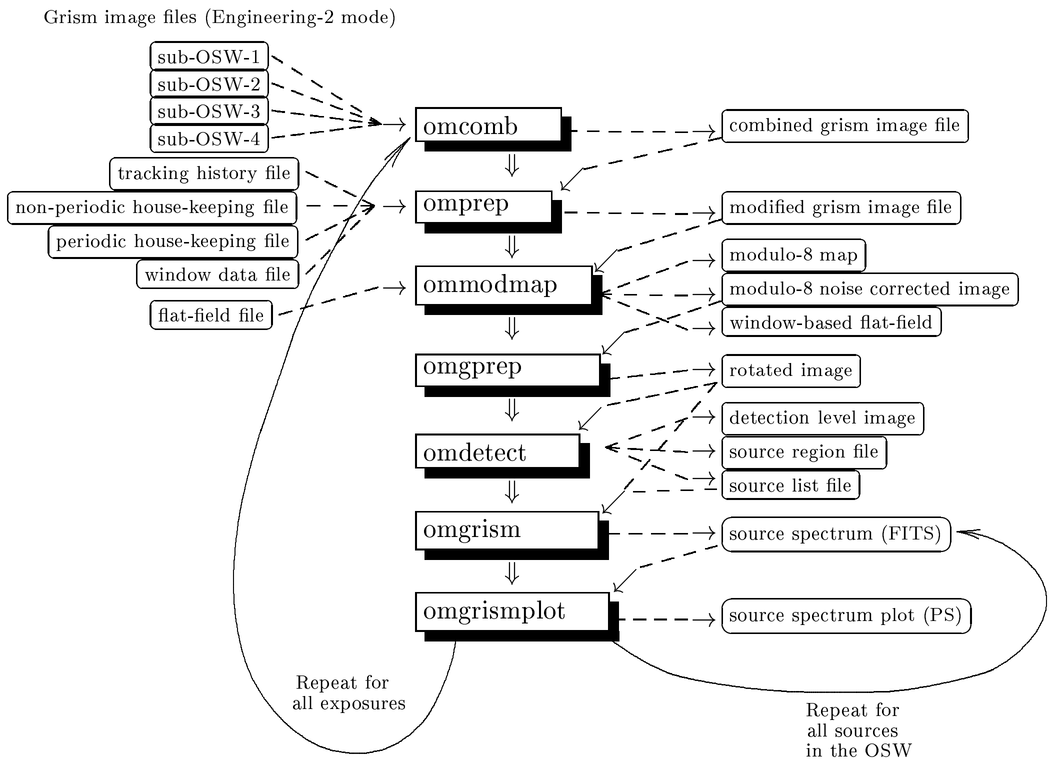


Figure 52: SAS processing chain for data acquired in the OM grism mode.

6.4.1 Grism specific tasks

Some of the tasks used in the processing of grism data are the same ones used in `omichain` and they perform the same functions and produce similar output. These tasks are `omcomb`, `omprep` and `ommodmap` (steps 0-1-2).

Other tasks are tools for spectroscopic data processing:

- `omgprep` (step 3) Grism images, as any other OM image, are affected by geometrical distortion which is corrected in the case of grisms by `omgprep` so as to obtain a linearised image. The grisms dispersion direction is inclined with respect to the detector axes. To facilitate the extraction of the spectrum, the image, after correcting it for distortion, is rotated so that the dispersion coincides with the Y axis. The rotation is done also by `omgprep`. The output from this task is a file (RIMAGE) from which spectral extraction can be done with any processing system. As it shall be described later, this file is the input for the interactive `omgsource`.

- `omdetect` (step 4). The same detection algorithm used in image mode data is applied to grism images coming from `omgprep` (RIMAGE) to search for spectral signatures, namely zero and first orders, present in the image. Each source is labelled as zero or first order depending on its shape. The results of the detection are written in a source list (SWSRLI) which contains the detected source positions in detector pixels in the rotated image. A `ds9` region file type (REGION) contains all performed detections.

- `omatt` (step 4.1). OM grism astrometry is performed using `omatt`. It is applied to the source list (SWSRLI) produced by `omdetect` to compute the astronomical coordinates of the detected spectra. New columns with RA/Dec positions are added to the source list for all detected zero and first orders. A north aligned grism image (SIMAGE) in sky coordinates is also produced.

- `omgrism` (step 5). Spectral extraction and calibration of the spectra is performed by `omgrism`. The source list generated by `omdetect` is analysed to search for the spectrum of the target. If it cannot be found at the proper position, then a default extraction is performed. The positions of the zero and first orders and a flag indicating the nature of the spectrum are written in another source list (SPECLI). A `ds9` region file type (SPCREG) depicts the zero and first orders.

  If the parameter `extractfieldspectra=yes` was set, then `omgrism` is used to establish correlations between the detected zero and first orders. The correlation is declared when the X coordinates of both orders are within a certain range and also their Y coordinates. After finding all the possible relations, the corresponding spectra are extracted. The proper identification of the zero order is essential since its position fixes the wavelength scale. In case a first order cannot be associated with a zero one, or Vice Versa, a default extraction is used. All detected zero and first orders are included in the SWSRLI source file, as well as the relations found among them. Only the successful ones giving rise to an extracted spectrum and the default extractions are written into the SPECLI source file and the SPCREG region file.

  The performed extraction is by default a box car, with predefined width and positions around the first order (or the Y coordinate of the zero order, if defaulted) for the spectrum and background regions. Signal weighted extraction is optional although its use is not currently recommended.

  The extracted net spectrum and the corresponding background are calibrated in wavelength and they are written to the output fits file (SPECTR) as count rate per angstrom in the whole spectral range contained in the image. Then the flux calibration, defined in a restricted wavelength range for each grism, is applied and the fluxed spectrum is written to the SPECTR fits file. The corresponding errors are also written to this file.

- `omgrismplot` (step 6). The produced spectra are plotted by `omgrismplot` in PDF and/or Postscript format. Net spectrum, background and fluxed spectrum are plotted. A picture showing the grism rotated image (RIMAGE) with the superimposed extraction regions (SPCREG) is also produced by `omgrismplot`.

6.4.2 Astrometry on grism images

As it has been mentioned in the previous section that the grism processing chain includes the astrometry task `omatt` so that the sources of all extracted spectra are assigned astronomical coordinates that facilitate their identification. This is particularly useful in case of multiobject spectroscopy (full frame observations). Since SAS v8.0 a sky aligned grism image is also produced.

6.4.3 Interactive spectral extraction

Sometimes spectra are very faint, or the desired spectrum is contaminated by other close zero or first orders, or there can be straylight features.These occurrences are not properly handled by the automatic processing done by `omgchain`. To circunvent these problems the user can apply `omgsource`. This task takes a rotated image coming from `omgprep`, displays it in the terminal and the user can select with the cursor the zero and corresponding first orders to be extracted. The extraction width and the background region definition can be changed as well so as to avoid contaminating features. The task passes the selected values to `omgrism` and the extraction and calibration continues. The user names the new source list and spectrum files.

The user selected position for the zero order can be refined by `omgsource` using a centroiding mechanism. Since the position of the zero order determines the wavelength scale, this centroiding can be turned off by the user in the case that close, contaminating features may perturb its results.

An existing source list can be loaded on top of the rotated image so as to check it and to modify it interactively.

6.4.4 Further notes on processing of OM grism data

OM grism data are complex, and a grism image can contain a lot of sources, zero and first spectral orders, in addition to complicated straylight features affecting the background and the spectra. This makes the automatic extraction process very difficult and prone to spurious detections and extractions. The user must check carefully the produced spectra. The source list of extracted spectra produced by `omgrism` is also represented in a `ds9` type region file (SPCREG) which can be overlaid on the rotated image to verify the correct extraction for the target spectrum or for all spectra in the field.

The SPECLI file tells us whether each extracted spectrum corresponds to the main target, or to a default extraction, or to a field object. The keyword OBJ_TYPE flags this also in the SPECTR file.

In case of problems or doubts, it is recommended to run the interactive `omgsource` after `omgprep`. This task uses as input the rotated image already mentioned.

The described rotated image RIMAGE contains all corrections proper to OM grism data. Therefore it can be used within any spectral reduction package or customised reduction system to perform the extraction of the spectrum, which can afterwards be calibrated using the contents of OM_GRISMCAL CCF.

It should be noted that coincidence loss corrections are currently not applied to grism data. Also, there is no correction for flux in the wings of the cross dispersion profile if the user selects interactively an extraction swath narrower than the base width of the spectrum.

Astrometric corrections are applied in grism data. The coordinates of the targets in the field of view corresponding to all extracted spectra (`extractfieldspectra=yes`) are written in the spectra source list and in the headers of the spectra files. It should be noted that these coordinates are less accurate than the ones obtained in normal image data using the lenticular filters (UVW2, UVM2, UVW1, U, B and V).

As of SAS 18, spectra extracted with `omgchain` are corrected for time-dependent sensitivity degradation, as with photometry data obtained with `omichain`. The scale of the correction is outlined in the SAS thread, OM data reduction with SAS: grism data processing chain, https://www.cosmos.esa.int/web/xmm-newton/sas-thread-omg

6.5 OM SAS processing products

This section provides a general description of the final products obtained when running the SAS chains on OM data.

The chains produce intermediate files that are sometimes overwritten by different tasks. They are recognised by the first letter of their name (”I” in `omichain`, ”F” in `omfchain`, ”g” and ”u” in `omgchain`). Their detailed descriptions can be found in the on-line documentation.

By running the tasks interactively, the user can maintain these intermediate products for a better understanding of the whole process.

OM processing chains and pipeline products are named as **zooooooooooOMueeettttttsxxx.fff**, where:

- z denotes final product (P: image or fast, p: grism) or intermediate file (I, F, g, u) as defined above
- oooooooooo stands for the observation ID,
- u is the exposure flag (S:scheduled, U:unsched, X:not applicable),
- eee is the exposure ID,
- tttttt is the data type,
- s is the OM window within the exposure,
- xxx is the source number within the window,
- fff is the file type (FIT, FTZ, PDF, PNG etc.).

In what follows, a data type by the tttttt identifier, e.g. tttttt= SIMAGE, is used for an OM sky image product. The window and source number identifier (sxxx) is omitted.

In combined images resulting from `ommosaic` or after processing the full frame image produced by `omcomb`, files with data type FIMAG_, FSIMAG, HSIMAG, LSIMAG and RSIMAG, "s" indicates the corresponding filter used. The optical filters are noted V, B and U, while L, M and S represent UVW1, UVM2 and UVW2 respectively.

There are two products associated with the tracking history files, namely the TSHPLT.PDF and the TSTRTS.FIT file. There are three data products per observing science window (OSW), namely IMAGE_.FIT, SIMAGE.FIT and SWSRLI.FIT. If fast mode data are present, there are two products per fast OSW, namely TIMESR.FIT and its graphics version TIMESR.PDF. There are two products generated on a per observation basis, which are FLAFLD.FIT and OBSMLI.FIT.

The standard pipeline does not run the chains `omichain`, `omfchain`, `omgchain` included in the SAS system. Similar chains using the same tasks, sometimes with different parameters, are run instead.

It should be noted that the pipeline produces compressed FITS files named .FTZ while the output obtained when the SAS chains are run by the user is not compressed, .FIT.

A brief description is given of the main files generated when running SAS. The user should be aware that there may be some differences in the naming of files produced by the standard pipeline (so-called **pps** products) run by the SOC and included into the XMM-Newton Science Archive. Also, intermediate files are deleted in the pipeline processing. Table 12 shows the current equivalence between both types of files.

- **TSHPLT.PDF file:** It provides a visualisation of the tracking history file. It gives an overview of the pointing stability in the course of an exposure. The drift history of an exposure is displayed as a vector diagram. Each data point represents the average attitude solution of one tracking frame, lasting typically 20 s. The pointing drift is calculated with respect to the OM attitude at the time where the reference frame was defined. The reference attitude of an exposure is determined at the beginning of a science exposure. Histograms at the side of the vector diagram show the projection of the OM pointing drift onto the x- and y-direction. The second output page shows the incremental OM drift between 2 subsequent tracking frames. A clustering of points at one location would indicate a systematic drift into one direction. Typically the pointing stability is better than 1 arcsec during one exposure, which corresponds to 2 pixels on the diagrams. There is one TSHPLT PDF file produced for each THX file in the ODF.

- **TSTRTS.FIT file:**. There is one TSTRTS FITS file produced for each THX file. The binary extension comprises n columns, i.e. one for each tracking star used. Each column lists the count rate (cts/s) of a tracking star averaged over the tracking frame duration. Each row indicates a new tracking frame, and one column corresponds to a time series of a specific star. The number of columns corresponds to the number of tracking stars used in an exposure. It can be any number up to 15.

- **IMAGE_.FIT file:** The Primary array contains the flatfield and mod8 corrected image. The header contains the WCS parameters applied to the raw image. The MODES extension lists the details of the window configuration. The QUALITY extension contains in an image the quality array. Any non-zero entry in the quality array reflects a bad pixel notified in the calibration bad pixel map or any location of the image where problems were encountered during the image processing. The pseudo images generated for fast mode windows follow the same naming.

- **QIMAG_.FIT, FQIMA_ files:** Produced since SAS v13.0, these files have the same structure as the previously defined **IMAGE_.FIT**. The QUALITY extension here contains much more complete information. These files are used in `omdetect` and they replaced, from SAS v14.0, the former ones, which were maintained for comparison.

- **SIMAGE.FIT file:** The primary array of this dataset contains the north-aligned sky image. The image is flatfielded, mod8 corrected, resampled and distortion corrected. WCS coordinates are contained as header keywords. Coincidence losses and dead time are not corrected in this image. The north-aligned sky pseudo images generated for fast mode windows and the sky aligned grism images follow the same naming.

- **SWSRLI.FIT file:** The primary header of an OSW source list file contains, besides the definition of the OSW within the exposure and the observation, the sensitivity limit of the plate expressed in count rates and in instrumental magnitudes. The binary extension holds the list of detected sources. There are the following entries for each detected source: identifier within the OSW, source position in pixel, source position in RA/Dec and galactic coordinates, the positional uncertainty, the extracted source count rates and its error estimate, the significance of the source detection, the aperture size used and the value of the PSF and coincidence loss corrections, the brightness in instrumental magnitudes, the shape of the source expressed as the two semi-axes of an ellipse (for point sources the two axes should agree), the orientation of the ellipse and three quality flags, describing whether the source is thought to be extended, confused or affected by bad pixels. The last entry is the source identifier in the final combined source list.

  In case of grisms the SWSRLI file contains the position and astronomical coordinates of the detected zero and first orders and their correlation if it has been found.

- **FLAFLD.FIT file:** This image is either part of the pipeline products or generated by `omflatgen`. There is one file per observation containing an image extension. The image describes the flatfield response covering the whole detector at coarse resolution. Since flat field correction is not needed, all pixels values are set to unity.

- **EVLIST.FIT file:** This is an intermediate events list produced when processing fast mode data

- **TIMESR.FIT file:** The time series contains source (background subtracted) and background rates and their error estimates as a function of time, within the specified time sampling. These time series are produced only for fast mode data.

- **TIMESR.PDF or .PS file:** The time series is plotted here to produce a graphic light curve, together with some statistics performed on the data.

- **OBSMLI.FIT file:** This file contains the combined source list for all OSWs of an observation. Information of sources whose spatial position coincides within the specified `nsigma` are merged together. An observation source identifier is assigned to each source, which can be used to look up the sources in OSW source lists (SWSRLI files). The list contains: the observation source identifier, the position in RA/Dec and galactic coordinates, the positional uncertainty, the detection significance and corrected count rates in the different filters, the source brightness expressed in instrumental magnitudes and its uncertainty, the quality, source extension and confusion flag for each filter, the characterisation and orientation of the spatial extent (described as in the SWSRLI files by the two semi-axes and the orientation angle with respect to the image x-axis) for each filter, and finally, if a transformation was possible, the source brightness in a standard photometric system, as well as the colour indices.

AB magnitudes and absolute fluxes for all filters are included as well.

If `omvariability` has been used, then two columns, filter_CHI2 and filter_MAXDEV provide variability information for detected sources.

- **omvariability.ps file:** `omvariability` produces this file containing plots showing the light curves of detected variable sources.
- **(FIMAG_, FSIMAG, HSIMAG, LSIMAG, RSIMAG, USIMAG).FIT files:** These are combined full frame or mosaiced images produced by merging images of different exposures obtained with the same filter.
- **(HSISWS, LSISWS, RSISWS, USISWS)x.FIT files:** Where x can be V, B, U, L, M, S are the equivalent to SWSRLI but obtained when running `omdetect` on mosaiced or stacked images of the filter x.
- **OBSMOS.FIT file:** Equivalent to OBSMLI but obtained when running `omsrclistcomb` on the RSISWSx source files obtained from mosaiced or stacked images.
- **OBSMER.FIT file:** Final combined source list obtained with `ommergelists`, where the new detections in OBSMOS are added to the original OBSMLI list.
- **RIMAGE_.FIT file:** The undistorted and rotated image produced by `omgprep` when processing grism data. It is the basis for the automatic spectral detection and extraction, and for interactive extraction with `omgsource`.
- **REGION.ASC file:** This is an ASCII version of the SWSRLI source list file (only the source positions) for use with `ds9` display.
- **SPECLI.FIT file:** This is similar to the SWSRLI file, but it contains only the zero and first order positions of the main target extracted spectrum, or if the parameter `extractfieldspectra=yes` was used, all final extracted spectra. For each extracted spectrum, the nature of the source is also given (Target, Field Object, Default Extraction,...)
- **SPCREG.ASC file:** This is an ASCII version of the SPECLI source list file (position, size and shape of the zero and first orders) for use with `ds9` display. A file **SPCREG.PS** shows the grism rotated image (RIMAGE) with the over-imposed extraction regions contained in the SPCREG.ASC file.
- **SPECTR.FIT file:** The extracted and calibrated spectra are written in this file. For each spectrum a table extension is given. In the table columns one can find:

```
        -  wavelength
        -  net spectrum (count rate)
        -  error in net spectrum
        -  background rate
        -  error in background
        -  flux calibrated spectrum
        -  error in flux
```

- **SPECTR.PDF / SPECTR.PS files:** They contain plots of the extracted spectra in the corresponding SPECTR.FIT file.

6.6 Running the OM data processing

The data package received by the investigator contains OM data which normally do not necessitate further processing for the purpose of calibration. However, a user may want to apply the most recent calibration, or to change some default parameters to e.g. improve the source detection on his/her data. It may not be necessary to run the complete chains, but just some tasks. All this can be done interactively.

The `SAS_ODF` environment variable shall be set to the directory containing the raw data, or directly to the SAS summary file, and access to calibration files shall be set through `cifbuild` (see § 2.3).

The OM tasks and chains can be run in a different working directory to that where the raw (ODF) data reside, providing that the environment variables are properly set.

Invoking `omichain`, `omfchain` or `omgchain` will automatically start the processing of all referred OM data. The duration of the process will depend on the number of exposures and windows, and at the end, the working directory will contain the processed files described before. Some intermediate files will be preserved as well.

Currently only `omichain` can accept parameters to limit the processing to a given filter or a given exposure:

```
    omichain filters=filters    (V, B, U, UVW1, UVM2, UVW2)

    omichain exposures=exposures   (letter S or U + exposure numbers)

  e.g.
          omichain filters=V
          omichain filters="U B V"
          omichain exposures=S006
          omichain exposures="S006 S007 U008"
```

Some of the default parameters used by individual tasks can also be tuned. To see all possible parameters, run:

```
    omichain -h
```

In the following examples, it is shown how to run all the tasks that form a chain. The fundamental parameters needed by each task are outlined. For a detailed description of all possible parameters, the user is referred to the section of the SAS online documentation with a description of all the SAS tasks at:

http://xmm-tools.cosmos.esa.int/external/sas/current/doc/

For a better understanding of the processing done by any of the chains, it is recommended to re-direct their screen output to a log file. This will allow the user to examine the process and to see if there is any error or anomaly.

If a user wants to fully understand the process, then running a chain task by task may be useful. In this case it is recommended to have the raw data to be processed and the auxiliary files in the working directory.

6.6.1 Example of image data processing

Due to the number of input parameters, lengthy file names, etc, it is not recommended to run any OM chain step by step. Only in special cases, some tasks, such as `omdetect`, `ommag`, `omatt`, `omsrclistcomb`, `lcplot`, may have to be run so as to fine tune some parameters. In some cases it might be more advantageous to use `omgsource` for grism data analysis.

To process task by task a single exposure in image mode, in addition to the house-keeping files listed in Table 10, the following files are needed:

```
0472_0125910501_SCX00000SUM.SAS  - ASCII observation summary file
0472_0125910501_SCX00000TCS.FIT  - Spacecraft Time correlation file
0472_0125910501_SCX00000RAS.ASC  - Spacecraft Raw Attitude file
0472_0125910501_OMS00400WDX.FIT  - Exposure priority window file
0472_0125910501_OMS00400THX.FIT  - Exposure tracking history file
0472_0125910501_OMS00400IMI.FIT  - Exposure image file to process
```

These files can be located in the working directory, or in any other one, providing that the environment variable `SAS_ODF` has been set accordingly. In our examples it is assumed that all necessary files are in the working directory.

The process will be run in the following way. Although, as said before, no real flat field correction exists for OM, nor it is necessary, the processing requires such a file which can be generated using the task `omflatgen` as follows.

```
step0> omflatgen outset=P0125910501OMX000FLAFLD0000.FIT
```

The output flatfield (primary extension) will be set to unity.

```
step1> omprep set=0472_0125910501_OMS00400THX.FIT \
              nphset=0472_0125910501_OMX00000NPH.FIT \
              pehset=0472_0125910501_OMX00000PEH.FIT \
              wdxset=0472_0125910501_OMS00400WDX.FIT \
              outset=tmp_tracking modeset=3
```

In case there is no THX file, then `set=DUMMYTHX.FIT`. `omprep` will generate a dummy file needed for the rest of the chain, with zero drift in it.

```
step2> omdrifthist set=tmp_tracking plotfile=P0125910501OMS004TSHPLT0000.ps

step3> omthconv thxset=tmp_tracking nphset=0472_0125910501_OMX00000NPH.FIT \
              outset=P0125910501OMS004TSTRTS0000.FIT  modeset=0

step4> omprep set=0472_0125910501_OMS00400IMI.FIT \
              nphset=0472_0125910501_OMX00000NPH.FIT \
              pehset=0472_0125910501_OMX00000PEH.FIT \
              wdxset=0472_0125910501_OMS00400WDX.FIT \
              outset=tmp_image_1 modeset=0

step5> omcosflag set=tmp_image_1 thxset=tmp_tracking \
                 samplefactor=1 timefactor=1


step6> omflatfield set=tmp_image_1 thxset=tmp_tracking \
                   inorbitflatset=P0125910501OMX000FLAFLD0000.FIT \
                   tsflatset=tmp_flat_field outset=tmp_image_2 \
                   samplefactor=1

step7> ommodmap set=tmp_image_2 mod8product=yes mod8set=tmp_mod8 \
                outset=P0125910501OMS004IMAGE_0000.FIT \
                nsig=3 nbox=16 mod8correction=1

step8> omqualitymap srclistset=' ' \
                    set=P0125910501OMS004IMAGE_0000.FIT \
                    outset=I0125910501OMS004QIMAG_0000.FIT \
                    mode=setqualityimage

step9> omdetect set=I0125910501OMS004QIMAG_0000.FIT \
                outset=P0125910501_OMS004SWSRLI0000.FIT \
                levelimage=level_image regionfile=region_file \
                nsigma=2 minsignificance=1 detectextended=yes

step10> omqualitymap srclistset=/P0125910501_OMS004SWSRLI0000.FIT \
                    set=I0125910501OMS004QIMAG_0000.FIT \
                    outset=P0125910501OMS004IMAGE_0000.FIT \
                    mode=setqualityimage


step11> ommag set=P0125910501_OMS004SWSRLI0000.FIT \

step12> omatt set=P0125910501OMS004IMAGE_0000.FIT \
              sourcelistset=P0125910501_OMS004SWSRLI0000.FIT \
              ppsoswset=P0125910501OMS004SIMAGE0000.FIT
```

The detected sources can be overlaid on the OSW by using `implot`, or `ds9`.

In the standard automatic SOC pipeline processing, the tmp_image files are re−used and thus overwritten. In the task by task processing, they are distinguished so that intermediate stage output can be inspected if desired. In the above example, product names are used where they are similarly used in the SOC pipeline.

The sky images of the multiple exposures corresponding to the default image configuration, as well as images in user defined mode with the same filter, can be combined in a single sky image of the field of view.

Starting with SAS 9, an additional detection can be done on mosaiced images. This will allow us to find fainter sources. The optional parameter `processmosaicedimages=yes` in `omichain` has to be used. Please refer to the on-line documentation for more details.

```
step13> ommosaic imagesets="list of sky images" \
                 mosaicedset=myfield_in_myfilter.fit
```

Finally, if multiple images with different filters are processed, the source lists can be combined as follows.

```
step14> omsrclistcomb sourcelistsets=P0125910501OMS004SWSRLI0000.FIT,..... \
                         nsigma=3 outset=P0125910501OMS000OBSMLI0000.FIT
```

where .... is a continuing list of SWSRLI files.

In case we have multiple exposures with the same filter(s) we can now run (since SAS 10) `omvariability`

```
step15> omvariability directorylist='' \
                      srclistsets='sourcelist1 sourcelist2 ...' \
                      obsset=P0125910501OMS000OBSMLI0000.FIT  \
                      plotfile=P0125910501OMLIGHTCURVE0000.ps  \
                      minstd=2 minnumcounterparts=2 nxsub=1 nysub=3   \
                      eflag=-1 cflag=-1 qflag=-1
```

If we want to search for fainter sources using mosaic or stacked images, after processing all of them and using these new images we continue as follows

```
step16> omdetect set=myfield_in_myfilter.FIT   \
                 outset=myfield_in_myfilter_RSISWSx_sourcelist.FIT  \
                 regionfile=mosaic_stacked_image.reg

step17> ommag set=mosaic_sourcelist.FIT

step18> omqualitymap srclistset=filter_mosaic_sourcelist.FIT  \
                     set=myfield_in_myfilter.FIT    \
                     outset=filter_mosaic_sourcelist.FIT   \
                     mode=usequalityimage
```

```
step19> omsrclistcomb sourcelistsets='list of filter_mosaic_RSISWSx_source_lists'  \
                      outset='combined_source_list_all_mosaic_images_OBSMOS.FIT'

step20> ommergelists srclist1=P0125910501OMS000OBSMLI0000.FIT  \
                     srclist2=combined_source_list_all_mosaic_images_OBSMOS.FIT   \
                     outset=myfield_inallfilters_merged_source_list_OBSMER.FIT
```

6.6.2 Example of fast mode data processing

In a similar way, if an exposure contains fast mode data, the following files will be needed,

```
0472_0125910501_OMS00400WDX.FIT  - Exposure priority window file
0472_0125910501_OMS00400THX.FIT  - Exposure tracking history file
0472_0125910501_OMS00401FAE.FIT  - Exposure fast mode data file
```

and the process can be run task by task in the following way,

```
step1> omprep set=0472_0125910501_OMS00400THX.FIT \
              nphset=0472_0125910501_OMX00000NPH.FIT \
              pehset=0472_0125910501_OMX00000PEH.FIT \
              wdxset=0472_0125910501_OMS00400WDX.FIT \
              outset=tmp_tracking modeset=3
```

As for image data, if there is no THX file, then `set=DUMMYTHX.FIT`. `omprep` will generate a dummy file needed for the rest of the chain, with zero drift in it.

```
step2> omdrifthist set=tmp_tracking plotfile=P0125910501OMS004TSHPLT0000.ps

step3> omthconv thxset=tmp_tracking modeset=1 \
                nphset=0472_0125910501_OMX00000NPH.FIT \
                outset=P0125910501OMS004TSTRTS0000.FIT

step4> omprep set=0472_0125910501_OMS00401FAE.FIT \
              nphset=0472_0125910501_OMX00000NPH.FIT \
              pehset=0472_0125910501_OMX00000PEH.FIT \
              wdxset=0472_0125910501_OMS00400WDX.FIT \
              outset=event_list.fit modeset=1
```

In its second run, `omprep` is invoked for fast data (`modeset=1`) and the FAE raw event data is transformed into a modified event list to be used as input for `evselect`,

```
step5> evselect table=event_list.fit xcolumn=RAWX ycolumn=RAWY \
                ximagebinsize=1 yimagebinsize=1 \
                withimageset=true imageset=raw_image.fit
```

The pseudo-image corresponding to the fast mode OSW has been created by this first run of `evselect`.

```
step6> omfastshift set=event_list.fit thxset=tmp_tracking \
                   nphset=0472_0125910501_OMX00000NPH.FIT
```

The X- and Y- coordinates of the photon events are corrected for spacecraft drift. New columns are added to the event list with the corrected values.

```
step7> omfastflat set=event_list.fit \
                  slewflatset=P0125910501OMX000FLAFLD0000.FIT \
                  oswflatset=fast_flat.fit \
                  fastimgset=P0125910501OMS002IMAGE_1000.FIT
```

Here, again, as for image mode processing, the system is prepared to apply a subset of the `omflatgen` generated flat field to the fast mode window data, taking into account the spacecraft drift. The flat field is set to one, and therefore this correction has no real effect. The task generates the tracking shifted `fast_flat.fit` (only for the fast mode window) and the corrected pseudo image `image.fit`.

```
step8 >omdetect set=P0125910501OMS004IMAGE_1000.FIT \
                regionfile=region_file nsigma=6 \
                outset=P0125910501OMS004SWSRLI1000.FIT
```

The output region will allow the user to check the proper detection of the source in the small fast window. The PSF information is used to parametrise the detected source.

```
step9> omatt set=P0125910501OMS004IMAGE_1000.FIT \
             sourcelistset=P0125910501OMS004SWSRLI1000.FIT \
             ppsoswset=P0125910501OMS004SIMAGE1000.FIT \
             usecat=no rotateimage=yes tolerance=3
```

Astrometry is applied as for image data. The pseudo-image is north aligned as well.

```
step10> omregion set=P0125910501OMS004SWSRLI1000.FIT \
                 srcnumber=1 srcradius=-6 nfwhm=3 bkginner=1.2 bkgouter=2.5 \
                 bkgfile=back_region.fit srcfile=source_region.fit
```

These regions will be used by `evselect` to filter out the event list and for extracting the corresponding photon events for the source and the background. Optional parameters can be used to fine-tune the definition of the regions.

```
step11> evselect table=event_list.fit xcolumn=CORR_X ycolumn=CORR_Y \
                 expression="((WIN_FLAG .eq. 0) .and. \
                 (region(source_region.fit, CORR_X, CORR_Y)))" \
                 maketimecolumn=T withrateset=Y timebinsize=10 \
                 rateset=source_rate.fit

step12> evselect table=event_list.fit xcolumn=CORR_X ycolumn=CORR_Y \
                 expression="((WIN_FLAG .eq. 0) .and. \
                 (region(back_region.fit, CORR_X, CORR_Y)))" \
                 maketimecolumn=T withrateset=Y timebinsize=10 \
                 rateset=back_rate.fit
```

And finally, the light curve can be obtained and plotted. The photometric corrections are also applied (coincidence loss, dead-time, PSF, magnitude conversion),

```
step13> omlcbuild srcregionset=source_region.fit bkgregionset=back_region.fit \
                  srcrateset=source_rate.fit bkgrateset=back_rate.fit \
                  sourcelistset=P0125910501OMS004SWSRLI1000.FIT \
                  wdxset=0472_0125910501_OMS00400WDX.FIT \
                  outset=P0125910501OMS004TIMESR1000.FIT \
                  bkgfromimage=yes
```

The optional parameter `bkgfromimage`, defaulted to yes in the call to `omichain`, allows the background to be measured in the associated image mode data or in the fast window data.

```
step14> lcplot set=P0125910501OMS004TIMESR1000.FIT \
               binsize=1 plotdevice=/PS bkgdyscale=no \
               plotfile=lightcurve.ps
```

For fast mode data, once exposure-level timeseries have been extracted, they can be concatenated using various tools. There is an OM SAS thread, Combining OM fast mode time series into a single data set, on this subject.

6.6.3 Example of grism data processing

As has been pointed out, OM grism data are image mode data. Since tracking corrections are not applied to grism data, spacecraft and summary files are needed:

```
0472_0125910501_OMS00500WDX.FIT  - Exposure priority window file
0472_0125910501_OMS00500IMI.FIT  - Exposure image file with grism data
```

and the process will be run in the following way,

```
step1> omprep set=0472_0125910501_OMS00500IMI.FIT \
              pehset=0472_0125910501_OMX00000PEH.FIT \
              nphset=0472_0125910501_OMX00000NPH.FIT \
              wdxset=0472_0125910501_OMS00500WDX.FIT \
              outset=g0125910501OMS005IMAGEI0000.FIT \
              modeset=4
```

The input image corresponds to a user defined window. In the case of full frame low resolution exposures, the task `omcomb` must be run beforehand and its output image be used as input for `omprep`,

```
step2> ommodmap set=g0125910501OMS005IMAGEI0000.FIT \
                mod8product=yes \
                mod8set=g0125910501OMS005MOD8MP0000.FIT \
                outset=g0125910501OMS005IMAGE_0000.FIT \
                outflatset=g0125910501OMS005FLAFLD0000.FIT \
                nsig=3 nbox=16 mod8correction=1
```

```
step3> omgprep set=g0125910501OMS005IMAGE_0000.FIT \
               outset=p0125910501OMS005RIMAGE0000.FIT \
               undistset=u0125910501OMS005IMAGE_0000.FIT
```

This undistorted and rotated image is the one from which the spectrum, or spectra, will be extracted.

```
step4> omdetect set=p0125910501OMS005RIMAGE0000.FIT \
                regionfile=g0125910501OMS005REGION0001.ASC \
                outset=p0125910501OMS005SWSRLI0001.FIT \
                nsigma=2
```

The source spectra have been detected. They can be checked by overplotting the region file on the rotated image, using `ds9`.

```
step5> omatt set=p0125910501OMS005RIMAGE0000.FIT \
             sourcelistset=p0125910501OMS005SWSRLI0001.FIT \
             ppsoswset=g0125910501OMS005SIMAGE0000.FIT \
             usecat=no rotateimage=yes tolerance=3 maxradecerr=1 maxrmsres=1.5
```

All detected spectra have been assigned RA and Dec. A sky, north aligned image is also produced.

Spectral extraction will be done now,

```
step6> omgrism set=p0125910501OMS005RIMAGE0000.FIT \
               sourcelistset=p0125910501OMS005SWSRLI0001.FIT \
               outset=p0125910501OMS005SPECTR0000.FIT \
               bkgoffsetleft=6 bkgwidthleft=-6 bkgoffsetright=6 \
               bkgwidthright=-6 spectrumhalfwidth=-6 spectrumsmoothlength=0 \
               extractionmode=0 extractfieldspectra=no \
               outspectralistset=p0125910501OMS005SPECLI0000.FIT \
               regionfile=p0125910501OMS005REGION0001.ASC \
               spectraregionfile=p0125910501OMS005SPCREG0001.ASC \
               addedregionfile=0
```

Target spectrum, or all spectra in the field of view if,

```
extractfieldspectra=yes
```

is used, are extracted and calibrated.

Finally, the results can be plotted,

```
step7> omgrismplot set=p0125910501OMS005SPECTR0000.FIT \
                   binsize=1 plotdevice=/PS \
                   plotfile=g0125910501OMS005SPECTR0000.PS \
                   scalebkgplot=no plotflux=2 \
                   spectraregionfile=p0125910501OMS005SPCREG0001.ASC \
                   regionplotfile=p0125910501OMS005SPCREG0001.PS \
                   rotatedimageset=p0125910501OMS005RIMAGE0000.FIT
```

A PDF version of the plot is also produced.

6.7 Analysing OM data

As has been pointed out already, OM data in image mode and fast mode with the normal filters, are fully processed by the SAS pipeline. All data, including the grisms can be run through the corresponding chain: for each exposure of a given observation, all necessary corrections are applied to the data files. Then a source detection algorithm is used to identify the sources present in the image. Standard aperture photometry is applied to obtain the count rates for all detected sources. These rates are corrected for coincidence losses, dead time and time dependent sensitivity degradation of the detector, and finally OM instrumental magnitudes and standard colour corrections are computed as well as absolute fluxes. A final source list is obtained from all exposures and filters. The detector geometric distortion correction and astrometric corrections are applied to each source's position, and also the whole image is converted to sky coordinates space and rotated so as to have the North on the top. Default image windows are also combined to obtain a mosaic (per filter) of the FOV. In the case of grism data, the spectra are searched for, extracted and calibrated in wavelength and absolute flux. Astrometry is also performed on grism data to compute the astronomical coordinates of the sources whose spectra have been extracted.

However, one has to be aware of some peculiarities of OM data before starting the analysis.

- **Artifacts**

  OM images show several artifacts. These artifacts are generally only visible when viewing the OM images in a high contrast and in logarithmic display (see the OM dedicated section of the UHB for some example images). Artifacts can however affect the accuracy of a measurement, e.g. by increasing the background level. The following artifacts may be present in the raw OM images.

  - Out of time events: very bright sources with count rates of several tens of counts per second show a strip of events along the readout direction. As the OM is a shutterless detector, these events correspond to out of time photons arriving while the detector is read out.

- "Smoke rings": bright sources generate smoke ring like structures, which are located radially away from the centre of the field of view. These rings are caused by photons which are reflected off the detector entrance window back onto the detector photocathode.
- Fixed pattern noise: raw OM images show a modulo 8 regular pattern originating from imperfections of the event centroiding algorithm in the instrument electronics. This modulo 8 pattern is removed during image analysis by the task `ommodmap`, if sufficient statistics are available in the image but this is not always possible for low count images (e.g. some UV filter images).
- Straylight features: straylight is caused by a chamfer in the OM detector housing which reflects light from outside the OM FOV onto the active detector area. The reflected celestial background light sums up onto a circular area with an increased background rate in the centre of the OM field of view. The light coming from bright sources at offaxis angles ∼12-13 arcmins and reflected by the chamfer can also produce loop like structures in an OM image. These loops can degenerate into long streaks depending on the source positions.

• **Grism Data**

  The complexity of grism data already mentioned earlier is increased by the presence of the artifacts described before (see § 6.4.4). Great care has to be taken when analysing the output products of grism data processing with SAS.

The following points should also be kept in mind:

1. The OM operates in photon counting mode but images are accumulated on board. Good time intervals (GTI) have no meaning in OM data. Either the full exposure is selected or discarded.
2. Contrary to the X-ray instruments, an OM exposure does not provide direct energy information except when grisms are selected.
3. As has been explained, a flatfield response of unity is assumed.
4. Coincidence losses can occur which depend on the source brightness and on the CCD frame rate. The frame rate itself depends on the selected configuration of the detector science and tracking windows. If two or more events are located close to each other within the same CCD readout frame, they are detected and counted as one event. Also when photon splashes overlap, a mis-location is given by the centroiding algorithm. Another consequence of coincidence losses is event depletion, occurring at high count rates around the central source position.
5. Corrections for coincidence losses and for detector deadtime are applied when aperture photometry is performed on the detected sources. These corrections are not applied to any of the produced images.
6. The OM filters do not form a proper photometric system. However the photometric calibration of the instrument, based on observations with OM and from the ground, allows the SAS to obtain standard U, B, V magnitudes and colours in the Johnson system. (This applies to stars. Extended objects should be treated with care.) For

the UV filters (UVW1, UVM2 and UVW2) AB Magnitudes have been defined in addition to the instrumental system. An absolute flux conversion is provided for all filters.

7. The OM point spread function (PSF) has wide wings. This is taken into account in the application of the calibration with SAS through the proper setting of photometric apertures. A similar approach has to be taken if one wants to make an independent processing and analysis of OM data using any other data reduction package.

8. Straylight features, already mentioned, complicate the background subtraction in some cases, specially when the target star is located in or close to a straylight feature.

9. Imaging and fast mode data are corrected for time sensitivity degradation, so that data of a given source (count rates, photometry) obtained at different epochs can be compared. As of SAS 18, grism data processing also corrects for time sensitivity degradation.

10. In dense fields or fields with complex background variations, such as where nebulosity is present, contamination of source extraction apertures and/or background regions may not be adequately accounted for.

11. Although the OM SAS software attempts to identify problems, such as where sources are affected by bad pixels, read-out streaks or nearby objects, and flag sources accordingly, the flagging process is not foolproof and there are situations where sources may have issues but remain unflagged, or vice versa. For example, in some cases, if a bright source causing a read-out streak is not within the imaged area, sources that lie on its read-out streak may not be flagged.

In principle, after SAS has been run there is no need for further data reduction. The observation source list should contain the calibrated data with their errors. Therefore, the user can proceed with the analysis and interpretation of the processed data. However, some checking is recommended to verify the consistency of the data output.

The whole data processing can be repeated easily by a Guest Observer or XSA user, should any calibration file be updated and/or, importantly, in case there is doubt about the reliability of the results. The processing chains or the pipeline, apply default options in all SAS tasks, which eventually can be changed by the GO in order to improve the quality of the results. In particular, the source detection is very sensitive to the artifacts that are common in OM.

In what follows, some checks are outlined that a user should perform on OM processed data (by the standard Pipeline or by running SAS), and the use of one of the tasks, `omdetect`, where the user can modify parameters affecting the source detection and therefore the overall results of the data analysis.

1. Checking `omichain` output products:

   - The first thing to do is to overlay the image source list onto the sky image. This can be achieved with `implot`, which will overplot the detected sources on the corresponding image, and it will allow checks that all sources are real and that the one(s) of interested has/have been properly identified. A new task, `srcdisplay` does the same job and it is more friendly to use. If the REGION files produced by `omdetect` have been preserved (in manual run of the chain or the task), then `ds9` can also be used to plot the detections on top of the image. If the background is strongly affected by straylight features, this check is very important.

- Inspection of the combined source list (e.g. using `fv`) will allow us to check that the sources of interest have been picked up in all the filters where they are visible and that the combined list contains colours and standard magnitudes for them.
- Special care should be taken in examining the quality flags assigned to all detected sources. Their meaning is described in detail in the SAS on-line documentation (task `omdetect`).
- Check the tracking corrections: although the pointing stability of XMM-Newton is very good, one can verify it by examining the corresponding tracking history PDF file.
- When there are several consecutive exposures in a given filter, different values of the frametime parameter (e.g. in the default image mode, where each of the 5 exposures has different frametime) can introduce a variation of a few percent in the count rate from one exposure to the next. This is due to the coincidence loss correction, which depends strongly on the frametime. The resulting jumps in average count rate may be more severe for bright sources.
- When there are several exposures with the same filter, `omichain` combines the corresponding images and then it attempts a deeper detection in the co-added image. New sources may appear as a consequence of the increase in S/N. However, these sources do not have a proper coincidence loss correction. Since the new detected sources are very faint, the error is only a few percent. Some of these new sources may be fake detections due to errors in the alignment of the images or to enhanced noise patterns. All these new sources are flagged in the final merged list (OBSMER file).
- If the observation was made after revolution 3224, check whether the source of interest is affected by the Jupiter patch (§ 6.7.7)

2. Checking `omfchain` output products:

   - Inspection of the light curves:
     One can look at the PDF files containing the light curves to check that there is some signal detected and measured (both in the source and in the background).
   - Checking the presence of source(s) in the fast window pseudo-image.
     This can be done easily by displaying this image with SAOImage (`ds9`) or `fv`. Another possibility is to overlay the detected sources onto the pseudo-image using the task `implot` or `ds9`.
   - Checking with `ds9`) or `fv`, the presence and centering of the source(s) in the fast window pseudo-image.
   - Using `bkgfromimage=yes` in `omichain` (or `omlcbuild` if running step by step) will give better results if the source is bright or if there are more than one sources in the fast mode window. This is the default since SAS 12.

- Jumps due to coincidence loss correction. A fast mode observation consists of a series of exposures with one or several filters. As discussed for default image mode, the different values of the frametime in consecutive exposures can produce jumps in the average count rate level from one exposure to the next. The effect can be more significant in fast mode data where jumps in the mean count rate between exposures of up to 10% may be present.
- Fast mode data can suffer from some issues related to poor centring of sources in the small fast mode window, such as can sometimes arise when field acquisition fails, when there are unusually large random pointing errors or where the provided target coordinates were inaccurate. These are described further in a technical note, Centring, drift and oscillation issues associated with OM fast mode observations.

3. Checking `omgchain` output products:

   - Checking the detection of zero and first orders

     The correct correlation of the zero and first order of the spectra is essential. It can be verified by displaying the rotated image and overlaying on it the detections from the SPCREG file with `ds9`. SAS 8.0 produces a picture of the grism image with superimposed extraction regions. The source list SPECLI file indicates also these correlations. If the users wants to analyse all detections, then REGION and SWSRLI files should be examined.
   - Position of zero order

     The position of the zero order (centroid) is the zero point of the wavelength scale. It should be verified, e.g. using `ds9` as pointed out before.
   - Identifying the spectra.

     The final spectra present in the SPECTR.FIT file can be identified as said before by overlaying the SPCREG file on the rotated image or by looking at the produced .PS file. In addition, the astronomical coordinates of the sources showing spectra are computed when running `omgchain`.

4. Improving the source detection:

   - For image data, if the source of interest is close to straylight features or to other sources it may not be detected with the default settings of the `omdetect` task. The parameters have to be changed: `nsigma` and `minsignificance` (see SAS documentation, or run `omdetect -h` for details)

     ```
     omdetect set=your_image.fit outset=your_sourcelist.fit \
               regionfile=your_region.dat nsigma=p minsignificance=q
     ```

     where `your_image.fit`, should have been produced by `ommodmap`. The default values for `nsigma` and `minsignificance` are 2 and 1, respectively.

     Invoking `omdetect` with `regionfile=your_region.dat` will allow a fast checking by overlaying the newly detected source positions on the image with `ds9` using the created region file.

- In case of fast mode, if there is more than one source in the fast window, then the detection will be affected and therefore the whole light curve as well. Some parameters have to be changed in `omdetect` as in the case of image mode (see the online SAS documentation, or run `omdetect -h` for details).

  Invoking `omdetect` with `regionfile=your_region.dat` will allow a quick check by overlaying the newly detected sources positions on the image with `ds9` using the created region file.

5. On grism data, as with normal image data, `omdetect` can be used to improve the detection. However, it is recommended to use `omgsource` to select the spectra interactively.

6.7.1 Astrometry in OM images

The task `omatt` takes an OM OSW source list, with source positions in pixels, and converts them into sky coordinates. In addition, the whole image is corrected for geometric detector distortion and rotated so as to become north-aligned. The task requires the user to enter the name of an OSW source list and its corresponding OSW image. The positional accuracy obtained in this way is of the order of 2 arcsec, this error being due in part to the residuals of the geometric distortion correction.

In its second action, `omatt` can use the USNO SA1 catalogue to compute and apply an astrometric correction. An excerpt from the catalogue for the field of interest can be provided by the user. In SAS v13.0, `omichain` can produce this catalogue file if the proper configuration for remote access has been set (see SAS on-line documentation). Note, an alternative, here, is to use the REFCAT file that is normally available amongst the pipeline products of an observation, which contains the relevant USNO extract. This file can be provided, via a parameter, to `omatt` or `omichain`. The OM pointing vector and field of view are used as parameters to make a search of the USNO file, which lists all catalogue stars in the field of view. Two synthetic images are constructed from the source list and the catalogue stars. A two-dimensional cross-correlation is performed on the images, and this 2D cross-correlation function is searched for its maximum, which gives x and y offsets in pixels between the OSW source list and the catalogue. This offset is used to correct the catalogue tangent plane coordinates. The nearest catalogue star to each source in the source list is then found. If this distance is smaller than a tolerance times the positional error, then it is assumed to be that catalogue star. If sufficient catalogue stars are identified, then a least-squares fit is performed to the catalogue positions, to yield more accurate astrometry. The source positions in RA/Dec are then written into the source list, along with the positional error (the pixel coordinates are retained in the source list). This correction is also applied to the sky north aligned images.

The task `omsrclistcomb` can also perform an astrometric correction similar to `omatt`. Now, the whole combined list is used. This allows us to obtain such a correction for sources detected in images with few sources (e.g. obtained with UV filters) where a solution cannot be found by `omatt`.

6.7.2 Counts conversion to magnitudes and fluxes

The task `ommag` converts the count rates to magnitudes in the appropriate instrumental bandpasses. The rates are taken from a source-list produced by `omdetect` or from a time series produced by `evselect`. The output file will be a FITS file identical to the input source-list or time-series except that the count-rates have been converted into instrumental magnitudes (in the specified filter bandpass: U, B, V, UVW1, UVM2, UVW2) and then written as an extra column in the original FITS file. The programme also estimates the limiting magnitude and writes the value in the FITS header.

Since SAS 5.4, flux conversion factors for U, B, V, UVW1, UVM2 and UVW2 filters are added in the keyword in the COLORMAG extension of the CCF file, OM_COLORTRANS. These flux conversion factors help users to get a rough direct estimation of flux (expressed in erg/cm^2/s/Å) from count rates.

For each filter, the flux (in erg/cm^2/s/Å) can be obtained multiplying the count rates (counts/s) from SAS by the following values:

These flux conversion values have been obtained from observations of white dwarfs standard stars. They reflect the current status of the OM in-flight calibration, and are therefore constantly verified and updated. The users should make sure that the most updated calibration is always employed.

It should also be pointed out that these flux conversion numbers can only provide an approximated measurement of the flux without an *a priori* knowledge of the spectral type. For a more accurate determination of the flux, the users will find in our SAS watchout page updated values of the flux conversion factors for a given spectral type.

6.7.3 Barycentric correction for fast mode data

As it is stated in the header of the TIMESR.FIT files(keyword TIMEREF = LOCAL), the time values in the time series files produced by processing OM data in Fast Mode refer to the XMM-Newton satellite system.

This time scale can be converted into a solar system barycenter time system by applying the barycentric correction with the SAS task `barycen`:

```
barycen withtable=yes table=tserie.fit:RATE
```

where tserie.fit is the light curve file obtained from `omfchain`.

The `barycen` task overwrites the TIME column in the original file. Therefore, it is recommended to copy it beforehand if one wants to keep the non-corrected timing.

It should be noted that for OM, `barycen` is applied to the time stamps of the light curve, and not to the arrival time of each individual photon. `barycen` will not work on OM Fast Mode events list files.

6.7.4 AB magnitude system and absolute fluxes for OM

The AB Magnitude system [36] has been implemented for OM. The general reprocessing pipeline products and SAS output files contain AB values for all detected sources. This is done by the `omsrclistcomb`, and the results are written in the OBSMLI source file as AB magnitudes in all filters.

In addition to the absolute flux conversion based on white dwarfs described in § 6.7.2, SAS computes a conversion from AB magnitudes to flux units whose results are also written in the OBSMLI combined source file for all filters.

6.7.5 OM response matrices

The OM response matrices for all filters (UVW2, UVM2, UVW1, U, B, V) have been obtained by computing the effective area of the instrument from ground laboratory measurements of its various components (mirror reflectivity, filter transmission, photocathode quantum efficiency, microchannel plates and detector efficiency,...). In order to match the observed in-flight response, fudge factors were necessary. Those fudge factors were obtained by observing a series of spectrophotometric standard stars.

Response matrices for the Visible and UV OM grisms have also been produced. The OM grisms have an absolute flux calibration in the form of an Inverse Sensitivity Function (ISF). The ISF provides a direct conversion from count rate in the extracted spectrum to absolute flux. This ISF can be easily converted into effective area for both grisms.

The complete set, as well as a concise description and usage guidelines can be obtained from,

http://www.cosmos.esa.int/web/xmm-newton/om-response-files

These response files will allow the users to make a combined spectral fitting of XMM-Newton Optical Monitor and X-ray data using packages such as `Xspec`.

6.7.6 Converting OM data to OGIP II format

The output of the OM chains contains brightness values for each source in units of count rates, magnitudes and fluxes. This information can be found in the source list file for each exposure. In addition, as we have seen there is a combined source list containing the brightness values for all exposures within an observation. Consistency checks of observed OM brightnesses with models that fit the X-ray data are thus possible with the combined source list alone.

To facilitate a graphical comparison of OM data with X-ray data in the form of a Spectral Energy Distribution (SED) or to fit a model to the combined X-ray and OM data, the SAS task `om2pha` produces a file in the OGIP II format that can be read into spectral fitting programs such as `Xspec`.

A detailed description of `om2pha` can be found in the OM corresponding thread, Converting OM data to OGIP II format. If OM data are to be analysed in combination with X-ray data, it may be easiest to do a complete run with `xmmextractor`.

6.7.7 The Jupiter patch

In XMM-Newton revolution 3224, two accidental exposures of Jupiter, with the V filter, were executed. Due to the extreme source intensity, this caused some persistent damage to the photocathode, resulting in a small patch of degraded sensitivity near the centre of the OM field of view. This is decsribed in the OM Calibration Status document. The patch is an elliptical region with major and minor axes of 105 arcsecs x 60 arcsecs, whose throughput is position and wavelength dependent but is depressed by as much as 35% in the V filter. Sources in the main part of the patch are flagged during SAS processing. However, sources in the outer wings of the patch are not currently flagged and this annular zone includes the location of the pn boresight, where many targets are located. At the pn boresight, the throughput is suppressed by around 8% in the V filter and a few percent in the UV filters. Importantly, at the current time, the effects of the patch are not corrected for in SAS processing. Users should be aware that, if observed after revolution 3224, the Jupiter patch could affect their sources of interest and they may need to allow for the impact of the degradation. Users should also note that grism spectra (especially targets observed in the default grism window) may be affected by the patch over limited wavelength ranges in both the UV and Visible grisms, by up to about 25%. Again, the impact of the patch on the grism data is not corrected for by the SAS, currently.

6.7.8 Concatenating fast mode timeseries

For fast mode data, once exposure-level timeseries have been extracted, they can be concatenated using various tools. There is an OM SAS thread, Combining OM fast mode time series into a single data set, on this subject.

File name	File Content	Usage
ASTROMET	coefficients for geometric distortion correction	omatt omdetect omdrifthist omgprep omgsource omphotom omsrclistcomb
BADPIX	bad pixels position, type of defect and the severity level	omcosflag omfastflat
BORESIGHT	alignment of the instruments and star tracker	omatt omgprep omgsource
COLORTRANS	coefficients for colour transformation into a standard system	ommag ommag omlcbuild omsrclistcomb
GRISMCAL	wavelength and flux calibrations for the grisms	omgrism
HKPARMINT	house keeping parameter ranges	ommag
LARGESCALESENS	flat field map (set to unity)	omflatgen
PHOTTONAT	correction coefficients of count rates for detector non-linearity and ageing	ommag omprep omdetect omlcbuild
PIXTOPIXSENS	flat field map (set to unity)	omflatgen
PSF1DRB	point spread function for each filter	ommag omdetect omlcbuild
DARKFRAME	dark current map	QLA
DIFFUSEGALA	intensity map of diffuse galactic emissions	PHS
QUICKMAG	a rough count to magnitude conversion table for different spectral types	QLA
ZODIACAL	intensity map of the zodiacal light and average spectrum	QLA
LINCOORD	parameters for calculations of instrument configuration	not used

Table 11: Calibration files of the Optical Monitor.

SAS name	PPS name	Description
TSHPLT	TSHPLT	OM tracking history plot
TSTRTS	TSTRTS	OM tracking star time series
IMAGE_	IMAGE_	OM OSW image (any filter or grism)
IMAGE_	IMAGEF	OM fast mode OSW image
SIMAGE	SIMAGE	OM OSW sky aligned image
SIMAGE	SIMAGF	OM fast mode OSW sky aligned image
REGION	SWSREG	OM OSW sources region file
REGION	SFSREG	OM fast mode OSW sources region file
SWSRLI	SWSRLI	OM OSW sources list
SWSRLI	SFSRLI	OM fast mode OSW sources list
TIMESR	TIMESR	OM fast mode OSW source time series
OBSMLI	OBSMLI	OM combined observation source list
FIMAG_	FIMAG_	OM combined full-frame image
FSIMAG	FSIMAG	OM combined full-frame sky image
HSIMAG	HSIMAG	OM full-frame HIRES sky image mosaic
LSIMAG	LSIMAG	OM full-frame LORES sky image mosaic
RSIMAG	RSIMAG	OM default mode sky image mosaic
USIMAG	USIMAG	OM user windows sky image mosaic
RSISWS	RSISWS	OM default mode source list from image mosaic
HSISWS	HSISWS	OM full-frame HIRES source list from image mosaic
LSISWS	LSISWS	OM full-frame LORES source list from image mosaic
USISWS	USISWS	OM user windows source list from image mosaic
OBSMOS	OBSMOS	OM mosaic merged sources list
OBSMER	none	OM final combined sources list: OBSMLI+OBSMOS
RIMAGE	GIMAGE	OM grism rotated image
SIMAGE	SIMAGE	OM grism OSW sky aligned image
SPECLI	SPECLI	OM grism spectra list
REGION	SGSREG	OM grism DS9 regions
SPCREG	SPCREG	OM grism DS9 spectrum regions
SPECTR	SPECTR	OM source extracted spectra
SWSRLI	SGSRLI	OM grism OSW sources list

Table 12: File name equivalence between direct SAS and Pipeline products for OM.

	V	B	U	UVW1	UVM2	UVW2
effective wavelength (Å)	5430	4500	3440	2910	2310	2120
flux conversion factors	2.49E-16	1.29E-16	1.94E-16	4.76E-16	2.20E-15	5.71E-15
WD magnitiude zero points	17.96	19.27	18.26	17.20	15.77	14.87

Table 13: OM filter effective wavelengths and the white dwarf (WD) based zero points and conversion factors from count rates to magnitudes and fluxes

7 Analysis chain for point-like sources

The purpose of the analysis chain `xmmextractor` is to produce high-level science products from the raw, uncalibrated, data files contained in the Observation Data File (ODF). While the automatic SOC product pipeline system (PPS) products can be used for scientific analysis, their calibration status may not be the most recent one, and the source extraction parameters are not adjusted to the particular requirements in an individual observation such as size and position of the background extraction region or pile up correction. With a single tool, it is possible to get all relevant science products for a given observation for all XMM-Newton cameras. The tool operates via a configuration file in xml format which will always by downward compatible. Once a new SAS version is released, the same configuration file can be used to update all science products using the same configuration file.

The long-term goal is to provide an interactive tool, but at this stage `xmmextractor` is a task that is still being developed. While basic usage, such an initial default processing of a given ODF with default parameters should work, some of the higher-level options may produce problems with the present version.

A more detailed description is available on the SAS Analysis Threads web page and in the package description of the `xmmextractor`.

7.1 `xmmextractor`

A general-purpose tool is provided with `xmmextractor`. Without detailed background knowledge of individual SAS tasks the raw ODF data can be reduced to calibrated events files and high-level science products for an individual point source in a given observation. These products will be based on the most recent calibration and on customised extraction parameters.

The current implementation of `xmmextractor` only works reliably without any parameters. A call without parameters produces a full extraction of all data from all instruments in all modes. When no parameters are specified, `xmmextractor` runs fully automatically using standard settings. These settings are stored in a configuration file in the Extensible Markup Language (XML) which can be used to re run the tool later with a newer SAS version and/or updated calibration. It can also be edited with a text editor to customise a new run.

By default, science files are produced for the target coordinates, but any other coordinates can be provided in decimal sky coordinates. The size and position of the source and background extraction regions are determined automatically using the optimisation procedure `eregionanalyse` (see § 4.7.6). As a first start, this is recommended.

After downloading the ODF from the XMM-Newton Science Archive and initialising the SAS according to § 2.3.1, the tool is simply launched with

```
xmmextractor >& screenoutput.log
```

where the screen output can be stored into a separate log file using the UNIX pipe command >&.

Note that the environment variables `SAS_CCF` and `SAS_ODF` need to be defined and *HEASOFT* has to be initialized.

7.1.1 Configuration file

Apart from the products described in § 7.1.2, a default configuration file is produced that allows the tool to be rerun with exactly the same configuration. A copy can be made to be modified with a text editor in order to customise the performance.

In order to use a customised configuration file, the task is called with:

```
xmmextractor paramfile=myconfig.xml >& screenoutput.log
```

An example of a default configuration file is given in figure 53. The first block, <`OBSERVATION`>, contains performance setup in the format: <`PARAM id="analysisoption" default="0:all"/`>, where the parameter name is given in quotes behind `id=` and the parameter value in quotes behind `default=`. The first parameter, `analysisoption`, determines which level of products are to be extracted. The default, `0:all`, indicates that the full analysis is performed. Other options allow extraction of only events files, only spectra or light curves, etc. All options are explained in the package description of `xmmextractor`. The remaining parameters are self-explanatory. The data reduction can be turned off for each instrument by changing <`default="yes"/`> to <`default="no"/`> behind the corresponding instrument for which no data analysis is desired.

The remaining blocks contain configuration information for each available instrument and are named <`INSTRUMENT value="...."/`>, where the name of the instrument is given in quotes. Within each instrument block, a separate block is present for each exposure, where the mode, exposure id, exposure time, and a flag whether or not this exposure is to be processed are given. Replacing <`process="yes"/`> to <`process="no"/`> means that the exposure is not processed. For each exposure, the products that the tool can produce are listed in blocks within which the task setup can be modified. Again, each `yes` can be replaced by `no` if not wanted. Parameter names and values can be modified. Not all details can be given here and can be found in the respective documentation for each task.

A default configuration file can also be created without running `xmmextractor`, using the command

```
odfParamCreator outputFileName=myconfig.xml
```

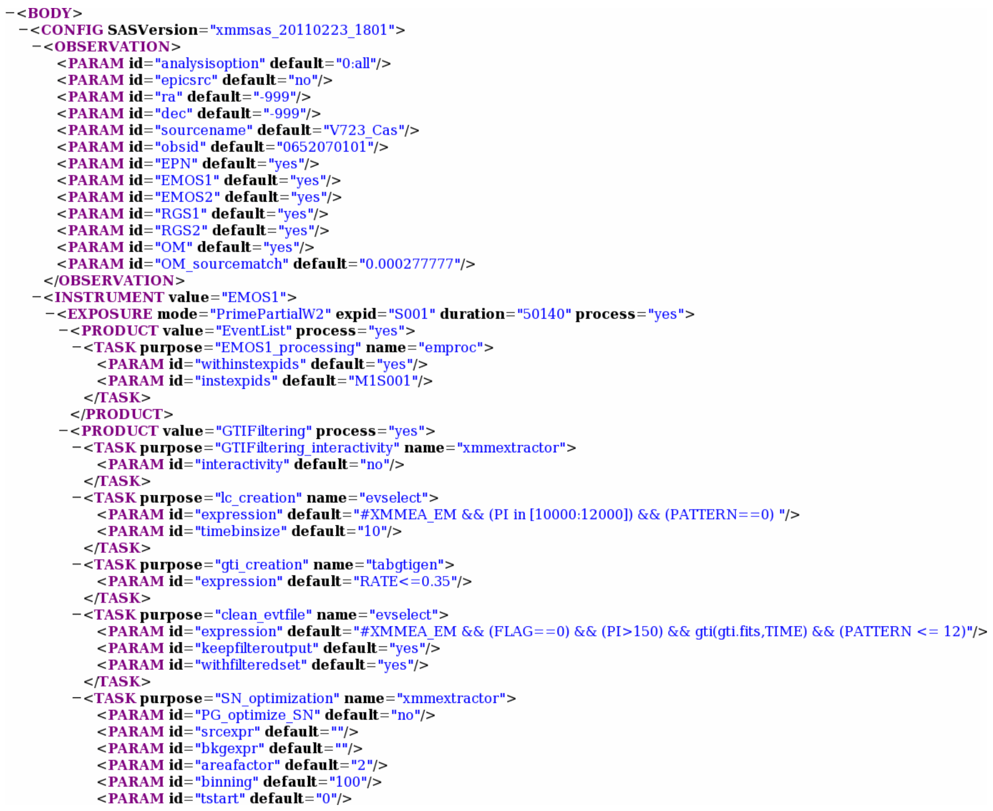
Note that the commands `cifbuild` and `odfingest` need to be run as part of the SAS setup before `odfParamCreator` can be used. For details, please see the description of the task `odfParamCreator`.

7.1.2 Output

Three log files are stored in the current working directory from where the tool is launched:

- xmmextractor.err: Containing errors
- xmmextractor.warn: Containing warnings
- xmmextractor.info: Containing runtime information

The output is stored in different subdirectories that are created in the current working directory from where the tool is launched. The output is organised in the following subdirectories:



```
-<BODY>
 -<CONFIG SASVersion="xmmsas_20110223_1801">
  -<OBSERVATION>
     <PARAM id="analysisoption" default="0:all"/>
     <PARAM id="epicsrc" default="no"/>
     <PARAM id="ra" default="-999"/>
     <PARAM id="dec" default="-999"/>
     <PARAM id="sourcename" default="V723_Cas"/>
     <PARAM id="obsid" default="0652070101"/>
     <PARAM id="EPN" default="yes"/>
     <PARAM id="EMOS1" default="yes"/>
     <PARAM id="EMOS2" default="yes"/>
     <PARAM id="RGS1" default="yes"/>
     <PARAM id="RGS2" default="yes"/>
     <PARAM id="OM" default="yes"/>
     <PARAM id="OM_sourcematch" default="0.000277777"/>
   </OBSERVATION>
  -<INSTRUMENT value="EMOS1">
    -<EXPOSURE mode="PrimePartialW2" expid="S001" duration="50140" process="yes">
      -<PRODUCT value="EventList" process="yes">
        -<TASK purpose="EMOS1_processing" name="emproc">
           <PARAM id="withinstexpids" default="yes"/>
           <PARAM id="instexpids" default="M1S001"/>
         </TASK>
       </PRODUCT>
      -<PRODUCT value="GTIFiltering" process="yes">
        -<TASK purpose="GTIFiltering_interactivity" name="xmmextractor">
           <PARAM id="interactivity" default="no"/>
         </TASK>
        -<TASK purpose="lc_creation" name="evselect">
           <PARAM id="expression" default="#XMMEA_EM && (PI in [10000:12000]) && (PATTERN==0) "/>
           <PARAM id="timebinsize" default="10"/>
         </TASK>
        -<TASK purpose="gti_creation" name="tabgtigen">
           <PARAM id="expression" default="RATE<=0.35"/>
         </TASK>
        -<TASK purpose="clean_evtfile" name="evselect">
           <PARAM id="expression" default="#XMMEA_EM && (FLAG==0) && (PI>150) && gti(gti.fits,TIME) && (PATTERN <= 12)"/>
           <PARAM id="keepfilteroutput" default="yes"/>
           <PARAM id="withfilteredset" default="yes"/>
         </TASK>
        -<TASK purpose="SN_optimization" name="xmmextractor">
           <PARAM id="PG_optimize_SN" default="no"/>
           <PARAM id="srcexpr" default=""/>
           <PARAM id="bkgexpr" default=""/>
           <PARAM id="areafactor" default="2"/>
           <PARAM id="binning" default="100"/>
           <PARAM id="tstart" default="0"/>
```

Figure 53: Example of a configuration file in xml format.

- `pn`, `mos`, RGS and OM : output of `epchain`, `emchain`, `rgsproc`, and `omichain`. If OM fast mode and/or grisms were used, the respective output of `omfchain` and `omgchain` will also be stored in the subdirectory *om/*. In particular, the fully calibrated events files for all EPIC cameras, RGS and OM fast mode (if used) can be found in these directories.
- `lcurve`: EPIC and RGS source and background plus background-subtracted light curves. For EPIC the source and background region files as well as a single region file containing both region definitions are also stored in this directory.
- `spectra`: Spectra and response matrices for all EPIC instrument (RGS spectra are in *rgs/* directory). Source and background region files as well as a single region file containing both region definitions are also stored for MOS1, MOS2, and pn in this directory.
- `epatplot`: diagnosis plot for pile up in EPIC instruments
- `images`: images of source regions for each sources found by edetect
- `gti`: Good Time Intervals used for time filtering (fits format)
- `results`: log files containing extraction parameters and science results

By default, all data from all instruments are analysed for the proposal coordinates. Other (sky) coordinates can be provided in decimal degrees using the parameters `ra` and `dec` in the configuration file. Seven analysis options are available, producing all products (default), only evens files, only doing gti correction (see below), only run `edetect_chain`, produce only EPIC spectra and/or light curves, and only produce RGS light curves. These options are specified by setting the parameter `analysisoption` to `0:all`, `1:events`, `2:gti`, `3:edetectchain`, `4:epic_spectra`, `5:epic_lightcurve`, or `6:rgs_lightcurve`. Analysis options 1-6 can only be used if events files are already present. For details, see the package description of `xmmextractor`.

An important step is to filter out intervals of high background in order to increase the signal to noise in EPIC spectra. This is described in § 4.4. Time intervals of high particle background are automatically excluded by `xmmextractor` using the criteria defined by the parameters defined in the <`TASK purpose="gti_creation" name="tabgtigen"`> corresponding subsections in the configuration file for each instrument.

The default parameters follow the recommendations in the documentation, but the flare background light curves stored in the subdirectory *gti/* should be checked to see if the standard parameters are appropriate for the specific observation. The gti correction is only done for EPIC *spectra* but not for *light curves*, because low signal-to-noise data are still better than gaps in a light curve.

For EPIC spectra and light curves, it is important to check for the presence of pile up. In § 4.5, a procedure is described how to assess the extent of pile up and how to correct for it. The first step is already done by `xmmextractor`. The diagnostics plots created by `epatplot` can be found in the subdirectory `epatplot`. If pile up is diagnosed, an annular source extraction has to be used. A user-defined format source extraction region can be communicated to `xmmextractor` by manipulating the corresponding expressions, <`PARAM id="srcexp" default="`*expr*`"`>, for each instrument where *expr* can be any region expression. The default is an annular extraction region with an inner radius of zero pixels, thus a circular region. The inner radius determined from following the pile-up thread [32] can be modified by hand before rerunning the tool.

In addition to pipeline processing of all products, interactivity modes are currently being developed. These will allow the user to define individual source- and background extraction regions on a displayed `ds9` image of the events file, define observation-specific good time intervals by looking at the particle background light curve, and perform pile up correction in an interactive iteration procedure.

[1] XMM-Newton Technical Description
http://www.cosmos.esa.int/web/xmm-newton/technical-details/

[2] XMM-Newton Serendipitous Source Catalogue
http://xmmssc.irap.omp.eu

[3] XMM-Newton Users Handbook
http://xmm-tools.cosmos.esa.int/external/xmm_user_support/documentation/uhb/

[4] XMM-Newton Science Archive
http://www.cosmos.esa.int/web/xmm-newton/xsa

[5] CCF Interface Control Document
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