Reducing RGS Data for Point-like Sources

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Abstract

This is a guide to the reduction of Reflection Grating Spectrometer (RGS) data for point-like sources with the XMM-Newton Science Analysis System (SAS). Important parameters from RGS tasks are explained. Sanity checks are described to the Guest Observer to verify that the RGS SAS processing performed correctly. A procedure to perform time-dependent spectroscopy is given as well.

1 Outline: XMM-Newton SAS 5.2 and latest

In the following, we will review the procedure to reduce Reflection Grating Spectrometer (RGS; den Herder et al. 2001 [2]) data of point-like sources with the RGS-oriented SAS tasks. Due to the rapid evolution of the RGS tasks in the SAS, a number of parameter names and default values have changed with time. In the following sections, we will explicitly explain the differences between SAS 5.2, and the current (as of November 2, 2001) development SAS ("latest") that will be released around January 2002. If not noted otherwise, the call to the tasks with SAS 5.2 or the "latest" are identical.

In this paper, the calling procedure of the tasks will be described as if the tasks were called from the shell; however, users can at any time adapt the procedure to their needs if they prefer to use the graphical user's interface, *gui*.

2 Prerequisite information: setting up the SAS

First, the user must define the appropriate SAS environments, `SAS_ODF` and `SAS_CCF`. We refer to the presentations by Giuseppe Vacanti on the start-up of the SAS, the use of *odfingest* and of *cifbuild* (see *gvacanti_1*, and *gvacanti_2*). Note that in case of problems the user may find it useful to set a high verbosity level, e.g., `setenv SAS_VERBOSITY 5` for csh/tcsh or `export SAS_VERBOSITY=5` for sh/bash.

Further information about the calibrations and the extraction of RGS data, can be found at http://xmm.vilspa.esa.es/calibration/.

3 The RGS metatask: *rgsproc*

The reduction of the RGS data uses about 15 SAS tasks. To facilitate the use of the XMM-Newton SAS, it is more comfortable (and recommended) to use the metatask, *rgsproc*, as an interface to the individual tasks. A number of parameter switches control the behavior of *rgsproc*, and are transferred to the tasks. In principle, default parameters have been set to obtain standard ouput files (see §4). The user is not required to launch *rgsproc* with specific changes to the parameters to obtain an event list (`filtered`) and spectra that can be used for quantitative analysis (see §6 for the generation of an RGS response matrix). We will however review a few important switchable parameters in the next section. The user is recommended to read the *rgsproc* documentation for a full description of its capabilities.

3.1 Important parameter switches

3.1.1 User-defined sources

rgsproc will generate two default source positions: `PROPOSAL` and `ONAXIS` (see *rgssources*). The entries can be found in the `sources` file, in the first table (`SRCLIST`). The `PROPOSAL` position is taken from coordinates provided by the Guest Observer at the time of the proposal submission. They are stored in the summary `ASCII` file generated by *odfingest* . The environment `SAS_ODF` must be defined to point to this file (see *gvacanti_1* and *gvacanti_2*). The `ONAXIS` position entry is calculated from the satellite attitude information. The `PROPOSAL` entry is per default the prime source (`#PRIMESRC`), and spectra are extracted for this “source” only. The user can also explicitely define the sky coordinates of the target. One then provides the right ascension and declination coordinates in degrees by means of the parameters `srcra`, `srcdec`, `label`, and `withsrc`. If `withsrc` = T, the user-defined source will *automatically* become the primary source.

```
rgsproc withsrc=T label='Capella' srcra=79.172329583 srcdec=45.997991
```

Note that it is possible to add sources from an EPIC-derived source list by means of parameters `withepicset` and `epicset`. The user can also provide dispersion and cross-dispersion coordinates instead of sky coordinates through `srcdisp` and `srcxdsp`.

3.1.2 Create spatial and order masks

In its default configuration, *rgsproc* will calculate and create region masks for the prime source (`#PRIMESRC`) in the CCD dispersion/cross-dispersion space (table `RGSi_SRCj_SPATIAL`, where i=1,2 corresponds to the RGS detector and j corresponds to the `INDEX` of the primary source in table `SRCLIST`), and in the dispersion/PI space (table `RGSi_SRCj_ORDER_k`, where i and j are the same as for the spatial mask, and k corresponds to the negative grating order). Finally, a spatial background (`RGSi_BACKGROUND`) is defined by excluding a certain percentage of the cross-dispersion PSF of the prime source, per default 95% (`xpsfexcl`). Note that the source spatial mask includes 90% (`xpsfincl`), and the order mask includes 90% of the pulse-height distribution (`pdistincl`). The parameter values can be varied: for example, `xpsfincl`=95, `xpsfexcl`=97, and `pdistincl`=95 are good alternatives. In its default configuration, *rgsproc* constructs order masks up to the second grating order (`orders`='1 2'), but this limit can be extended for bright, hard sources.

Note that, assuming the user takes a source list from the EPIC analysis, it is possible to define which source needs to be included for the generation of the masks, or which sources should be excluded from the background. The relevant parameters are `procsrcsexpr` and `exclsrcsexpr`. Boolean expressions must be used, e.g. by specifying the `INDEX` numbers of the sources in `SRCLIST`. An example with two sources is given in §8.

3.1.3 Flow control/entry stages

The `instruments` switch allows the user to define whether RGS1, RGS2 or both should be processed. The default is both, i.e. `instruments`='RGS1 RGS2'. The only effect is that *rgsproc* will last longer, and both RGS1 and RGS2 files will be created in the same directory.

A number of parameters of the flow control differ in SAS 5.2 and "latest":

3.1.3.1 SAS 5.2 The *rgsproc* flow in SAS 5.2 runs through four stages: in brief, a) the processing of individual CCD event files and their merging into a single file, b) the creation of a source list file and the application of aspect drift corrections, c) the filtering of the data and calculation of the exposure maps, d) the calculation of the masks and generation of the background-corrected net spectra. If the *rgsproc* call has been interrupted for any reason, it is always possible to re-enter at a certain stage, under the condition that the previous stage has finished. Re-entry takes place by means of the boolean parameters `processevents`, `processsources`, `processexposure`, and `processregions`. They play a key role for time-dependent spectroscopy (see §7).

3.1.3.2 "Latest" The *rgsproc* flow of the "latest" SAS is similar to that of SAS 5.2, with an additional entry stage, the "fluxing" stage which generates dummy response matrices and constructs fluxed spectra. Instead of five different boolean parameters, only two parameters define the entry (`entrystage`) and the final (`finalstage`) stages. The allowed values are 'events', 'angles', 'filter', 'spectra', and 'fluxing'. Again, their role is important for time-dependent spectroscopy (see §7). The parameter `expunge` deletes intermediate files such as the 'events' files (default) or the 'merged' file. Note that the latter is required to perform time-dependent spectroscopy, therefore it is recommend to keep it. Finally, the user can add a prefix to the filenames generated by the "latest" SAS (`withprefix` and `prefix`). For example, the revolution number can be added, since it has been abandoned for the "latest" SAS (see §4).

4 Filenames

Let us assume that *rgsproc* has been executed with its default configuration and that the RGS data of Capella (revolution 0232, observation identification number 0134720101) have been used. The user will find the following files in the current directory (note that CCD4 on RGS2 and CCD7 for RGS1 are not available from revolutions 28 and 137 onward, respectively, see den Herder et al. 2001 [2]).

4.1 SAS 5.2

0232_0134720101_R1S00701_events.ds	CCD 1 event file for RGS1
0232_0134720101_R1S00702_events.ds	CCD 2 event file for RGS1
0232_0134720101_R1S00703_events.ds	CCD 3 event file for RGS1
0232_0134720101_R1S00704_events.ds	CCD 4 event file for RGS1
0232_0134720101_R1S00705_events.ds	CCD 5 event file for RGS1
0232_0134720101_R1S00706_events.ds	CCD 6 event file for RGS1
0232_0134720101_R1S00708_events.ds	CCD 8 event file for RGS1
0232_0134720101_R1S00709_events.ds	CCD 9 event file for RGS1
0232_0134720101_R1S00700_sources.ds	Source file for RGS1
0232_0134720101_R1S00700_merged.ds	CCD merged event file for RGS1
0232_0134720101_R1S00700_filtered.ds	filtered event list for RGS1
0232_0134720101_R1S00700_expmap.ds	combined exposure map for RGS1
0232_0134720101_R1S00700_net1o1.pha	first-order net RGS1 spectrum for source 1
0232_0134720101_R1S00700_net1o2.pha	second-order net RGS1 spectrum for source 1
0232_0134720101_R1S00700_bkg1o1.pha	first-order background RGS1 spectrum excluding source 1
0232_0134720101_R1S00700_bkg1o2.pha	second-order background RGS1 spectrum excluding source 1
0232_0134720101_R2S00801_events.ds	CCD 1 event file for RGS2
0232_0134720101_R2S00802_events.ds	CCD 2 event file for RGS2
0232_0134720101_R2S00803_events.ds	CCD 3 event file for RGS2
0232_0134720101_R2S00805_events.ds	CCD 5 event file for RGS2
0232_0134720101_R2S00806_events.ds	CCD 6 event file for RGS2
0232_0134720101_R2S00807_events.ds	CCD 7 event file for RGS2
0232_0134720101_R2S00808_events.ds	CCD 8 event file for RGS2
0232_0134720101_R2S00809_events.ds	CCD 9 event file for RGS2
0232_0134720101_R2S00800_sources.ds	Source file for RGS2
0232_0134720101_R2S00800_merged.ds	CCD merged event file for RGS2
0232_0134720101_R2S00800_filtered.ds	filtered event list for RGS2
0232_0134720101_R2S00800_expmap.ds	combined exposure map for RGS2
0232_0134720101_R2S00800_net1o1.pha	first-order net RGS2 spectrum for source 1
0232_0134720101_R2S00800_net1o2.pha	second-order net RGS2 spectrum for source 1
0232_0134720101_R2S00800_bkg1o1.pha	first-order background RGS2 spectrum excluding source 1
0232_0134720101_R2S00800_bkg1o2.pha	second-order background RGS2 spectrum excluding source 1
0232_0134720101_SCX00000_attitude.ds	attitude file

4.2 "Latest" SAS

P0134720101R1S007SRCLI_0000.FIT	Source file for RGS1
P0134720101R1S007merged0000.FIT	CCD merged event file for RGS1
P0134720101R1S007EVENLI0000.FIT	filtered event list for RGS1
P0134720101R1S007EXPMAP0000.FIT	combined exposure map for RGS1
P0134720101R1S007SRSPEC1001.FIT	first-order net RGS1 spectrum for source 1
P0134720101R1S007SRSPEC2001.FIT	second-order net RGS1 spectrum for source 1
P0134720101R1S007BGSPEC1001.FIT	first-order background RGS1 spectrum excluding source 1
P0134720101R1S007BGSPEC2001.FIT	second-order background RGS1 spectrum excluding source 1
P0134720101R1S007matrix1001.FIT	first-order RGS1 matrix for source 1
P0134720101R1S007matrix2001.FIT	second-order RGS1 matrix for source 1
P0134720101R1X000hkgti_0000.FIT	housekeeping GTI table for RGS1
P0134720101R2S008SRCLI_0000.FIT	Source file for RGS2
P0134720101R2S008merged0000.FIT	CCD merged event file for RGS2
P0134720101R2S008EVENLI0000.FIT	filtered event list for RGS2
P0134720101R2S008EXPMAP0000.FIT	combined exposure map for RGS2
P0134720101R2S008SRSPEC1001.FIT	first-order net RGS2 spectrum for source 1
P0134720101R2S008SRSPEC2001.FIT	second-order net RGS2 spectrum for source 1
P0134720101R2S008BGSPEC1001.FIT	first-order background RGS2 spectrum excluding source 1
P0134720101R2S008BGSPEC2001.FIT	second-order background RGS2 spectrum excluding source 1
P0134720101R2S008matrix1001.FIT	first-order RGS2 matrix for source 1
P0134720101R2S008matrix2001.FIT	second-order RGS2 matrix for source 1
P0134720101R2X000hkgti_0000.FIT	housekeeping GTI table for RGS2
P0134720101OBX000fluxed1000.FIT	first-order RGS2 fluxed spectrum for source 1
P0134720101OBX000fluxed2000.FIT	second-order RGS2 fluxed spectrum for source 1
P0134720101OBX000ATTTSR0000.FIT	attitude time-series data
P0134720101OBX000attgti0000.FIT	attitude-drift GTI table

5 Validity checks

It is recommended that the user checks the validity of the *rgsproc* process. In particular, the spatial and order masks should be checked. This can be accomplished by creating a spatial image (`xcolumn`='BETA_CORR' an `ycolumn`='XDSP_CORR') and an order image (`xcolumn`='BETA_CORR' an `ycolumn`='PI') for each spectrometer. The task *evselect* must be used, as illustrated in the following for RGS1.

```
SAS 5.2: evselect attributestocopy='BETA_REF BETA_WID'    \
            table='0232_0134720101_R1S00700_filtered.ds'  \
            withimageset=T imageset='spatial_image.fits'  \
            xcolumn='BETA_CORR' ycolumn='XDSP_CORR'       \
            withxranges=T ximagemin=0.03 ximagemax=0.08   \
            withyranges=T yimagemin=-7.e-4 yimagemax=7.e-4

         evselect attributestocopy='BETA_REF BETA_WID'    \
            table='0232_0134720101_R1S00700_filtered.ds'  \
            withimageset=T imageset='order_image.fits'    \
            xcolumn='BETA_CORR' ycolumn='PI'              \
            withxranges=T ximagemin=0.03 ximagemax=0.08   \
            withyranges=T yimagemin=0 yimagemax=3500
```

```
latest:  evselect attributestocopy='BETA_REF BETA_WID'    \
            table='P0134720101R1S00700EVENLI0000.FIT'     \
            withimageset=T imageset='spatial_image.fits'  \
            withxranges=T ximagemin=0.03 ximagemax=0.08   \
            withyranges=T yimagemin=-7.e-4 yimagemax=7.e-4

         evselect attributestocopy='BETA_REF BETA_WID'    \
            table='P0134720101R1S00700EVENLI0000.FIT'     \
            withimageset=T imageset='order_image.fits'    \
            xcolumn='BETA_CORR' ycolumn='PI'              \
            withxranges=T ximagemin=0.03 ximagemax=0.08   \
            withyranges=T yimagemin=0 yimagemax=3500
```

The task *rgsimplot* can then overplot the region masks on the images. The output image from *rgsimplot* is shown in Figure 1. The user can visually verify that the masks are correctly aligned with the source.

```
SAS 5.2: rgsimplot withspatialset=T spatialset='spatial_image.fits' \
            withendispset=T endispset='order_image.fits'            \
            withspatialregionsets=T withendispregionsets=T          \
            srclistset='0232_0134720101_R1S00700_sources.ds'        \
            colourmap='SQRT' device='/XW' srcidlist='1'

latest:  rgsimplot withspatialset=T spatialset='spatial_image.fits' \
            withendispset=T endispset='order_image.fits'            \
            withspatialregionsets=T withendispregionsets=T          \
            srclistset='P0134720101R1S00700SRCLI_0000.FIT'          \
            colourmap='SQRT' device='/XW' srcidlist='1'
```

6 Spectral files and response matrix generation

The RGS spectra are `OGIP`-compliant, and can be analyzed in spectral fitting packages such as `XSPEC` or `SPEX`. In SAS 5.2, the spectrum consists of a count rate column, `RATE`, while in the "latest", the new format is in `COUNTS` with an additional column, `AREASCAL`, giving the area scaling factors. The version 11.1 (or higher) of `XSPEC` (`LHEASOFT 5.1` or higher) must be used with the latter format.

To analyze RGS data, the user must create an RGS response matrix for each source (e.g., `source`=1), order (e.g., `order`=1), and detector with SAS 5.2. With the "latest" SAS, a dummy response matrix is created at the 'fluxing' stage; however, it must *not* be used to perform a quantitative spectral analysis. Indeed, its default energy resolution (`rmfbins`=250 with *rgsproc*) is insufficient. The user can either directly create a proper response matrix in the 'fluxing' step of *rgsproc* or use the *rgsrmfgen* task. It is is recommended to use at least 4000 energy bins (`ebins`=4000 with *rgsrmfgen* or `rmfbins`=4000 with *rgsproc*). Note that, per default, the contribution of the cross-dispersion PSF in the background region is subtracted (in proper proportion) from the contribution in the foreground (extraction) region (`withbackground`=F). Below, we provide an example of the generation of a first order RGS1 response matrix for SAS 5.2 and the "latest" by *rgsrmfgen*.

```
SAS 5.2: rgsrmfgen ebins=4000 file='r1o1src1.rmf' order=1              \
            set='0232_0134720101_R1S00700_filtered.ds' withbackground=F \
            sourceset='0232_0134720101_R1S00700_sources.ds' source=1    \
            withspectrum=T spectrumset='0232_0134720101_R1S00700_net1o1.pha'
```

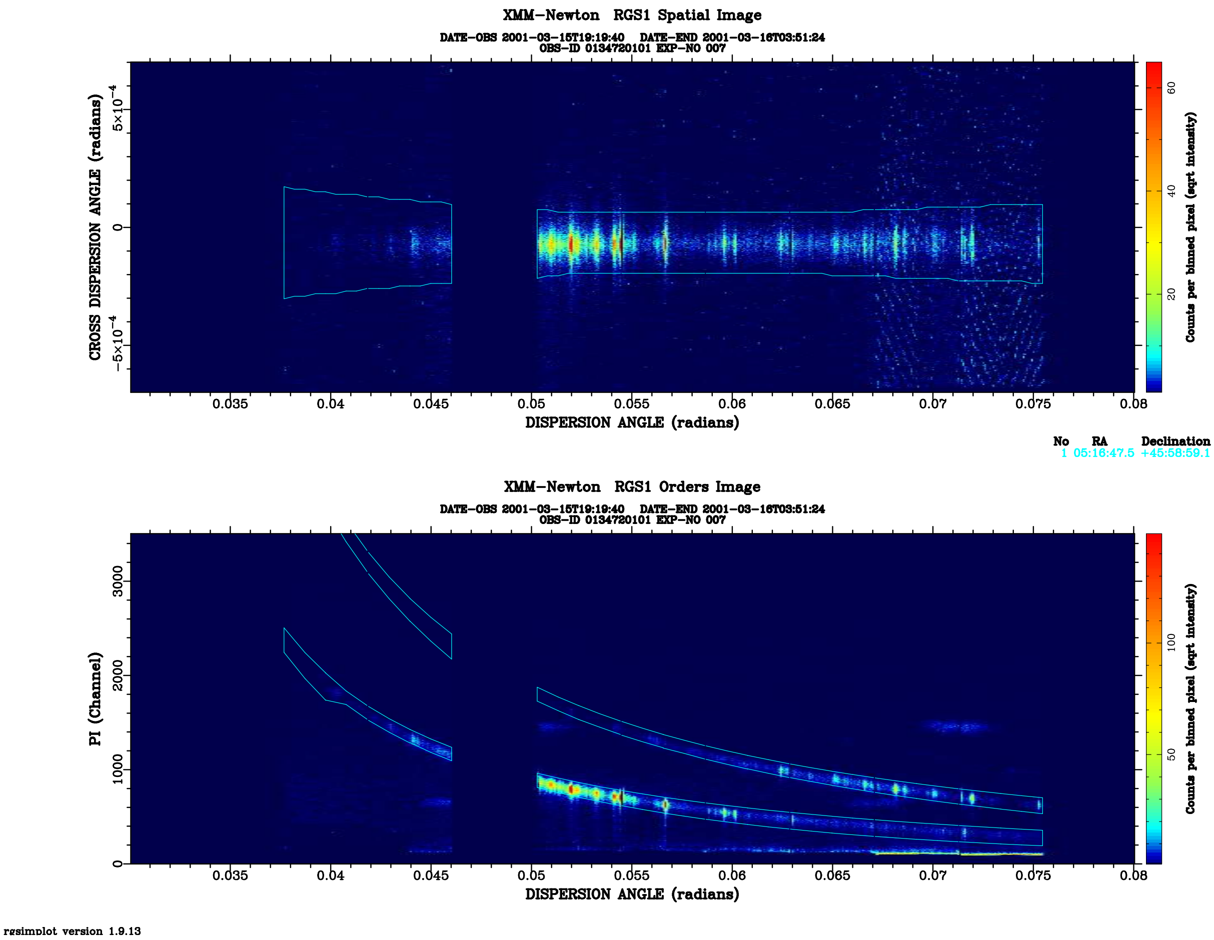

Figure 1: Output of *rgsimplot* for the Capella observation (rev 0232, obsID 0134720101, RGS1) showing the detector image with the spatial mask overlaid (top panel), and the order image with the first and second order masks overlaid (bottom panel).

```
latest:  rgsrmfgen ebins=4000 file='r1o1src1.rmf' order=1                \
            evlist='P0134720101R1S007EVENLI0000.FIT' withbackground=F    \
            srclist='P0134720101R1S007SRCLI_0000.FIT' source=1 fftdim=3 \
            withspectrum=T spectrumset='P0134720101R1S007BGSPEC11.FIT'
```

7 Time-dependent spectroscopy

When a source is variable, the user may want to perform time-dependent spectroscopy with the RGS. The basic idea is to apply a time selection by means of an auxiliary GTI table. However, assuming *rgsproc* has been run at least once, the user does not need to re-calibrate the data for each CCD, and re-apply aspect corrections. The user can then start *rgsproc* at the filter stage, using the `merged` file as starting point. A new `filtered` event list and exposure map will be created, and new time-dependent spectra will be extracted. Afterwards, another time selection can be applied by means of a new GTI table; the user is however advised to move the output files from the former selection in a subdirectory, as *rgsproc* will overwrite any existing file.

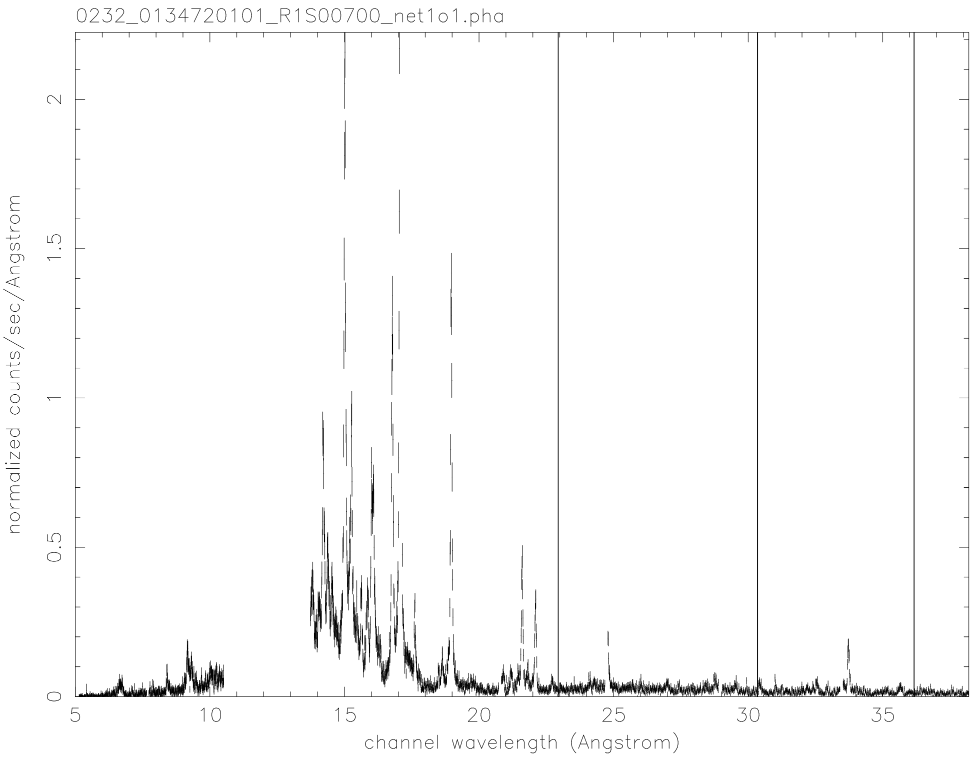

Figure 2: First order RGS1 spectrum of Capella plotted with XSPEC/QDP. Note the presence of a few single bins with very large error bars, due to the calculation of Rowland angles in single precision in SAS 5.2. The "latest" SAS performs the calculation in double precision, therefore such bins should not appear. For a discussion of the spectrum, see Audard et al. (2001) [1].

Using the Capella data, let us assume that we would like to extract spectra for TIME=[70419000,70429000]. This range brackets frame timestamps in seconds after MJD 50814. We first need to put the GTI information in an ASCII file, and then use *gtibuild* to transform it into a FITS GTI table.

```
echo "70419000 70429000" > gti.txt ; gtibuild file='gti.txt' table='gti.ds'
```

We then run *rgsproc* from the filter stage and use the GTI table:

```
SAS 5.2:  rgsproc processevents=F processsources=F processexposure=T processregions=T \
            withauxgti=T gtitable='gti.ds'

latest:   rgsproc entrystage='filter' finalstage='fluxing' auxgtitables='gti.ds'
```

Formally, the user should always use the latest exposure maps in the filtered event list to create an RGS response matrix; practically, however, an observation is usually stable enough to require only one response matrix for an average or a time-dependent spectrum.

8 Multiple sources: the example of YY Gem/Castor

In most cases, the prime target is the only source detected in the RGS. However, it is possible that a second source lies sufficiently far from the prime source in the cross-dispersion direction so that separate spectra can be obtained. Apart from including the secondary source in our science analysis, it must also be excluded from the background of the primary source!

The YY Gem/Castor observation (revolution 69, observation identification 0123710101) was planned such that both objects were almost parallel to cross-dispersion direction (Fig. 3), separated by 71″. For an analysis of the data, the user is referred to Güdel et al. (2001) [3]. Assuming the proposal coordinates of the prime source (YY Gem) are sufficiently accurate, it is only necessary to add the coordinates of the secondary source (Castor). We will provide below a procedure, step-by-step.

First, the data must be processed up to the filtering stage.

```
SAS 5.2: rgsproc processsources=T processevents=T processexposure=T processregions=F

latest:  rgsproc entrystage='events' finalstage='filter'
```

Then, *rgssources* is used to add (`filemode`='modify') the Castor entry in the `SRCLIST` table (`INDEX`=3) and keep the YY Gem `PROPOSAL` entry as the prime source (`userasprime`=F `changeprime`=F). *rgsproc* is not used with the `withsrc` switch (see §3.1.1), as the new entry would immediately be flagged as the primary source, which is not the purpose here. The following step needs to be repeated for both RGS1 and RGS2 (`instrument` parameter).

```
SAS 5.2: rgssources addusersource=T filemode='modify'        \
            instrument='rgs1' userasprime=F changeprime=F   \
            atthkset='0069_0123710101_SCX00000_attitude.ds' \
            rgsset='0069_0123710101_R1S00400_sources.ds'    \
            ra=113.6494283 dec=31.8882764 label='Castor'

latest:  rgssources addusersource=yes filemode='modify'      \
            instrument='rgs1' userasprime=F changeprime=F   \
            atthkset='P0123710101OBX000ATTTSR0000.FIT'      \
            srclist='P0123710101R1S004SRCLI_0000.FIT'       \
            ra=113.6494283 dec=31.8882764 label='Castor'
```

rgsproc can then be launched again at the stage of creating regions masks. At this stage it is important to inform *rgsproc* that both the prime source (`INDEX`==`#PRIMESRC`) and the new Castor entry (`INDEX`==3) need to be excluded from the background and that their region masks need to be calculated.

```
SAS 5.2: rgsproc processsources=F processevents=F processexposure=F processregions=T \
  exclsrcsexpr='INDEX==#PRIMESRC||INDEX==3' procsrcsexpr='INDEX==#PRIMESRC||INDEX==3'

latest:  rgsproc entrystage='spectra' finalstage='fluxing'                           \
  exclsrcsexpr='INDEX==#PRIMESRC||INDEX==3' procsrcsexpr='INDEX==#PRIMESRC||INDEX==3'
```

9 Fluxed spectra: combining RGS1 and RGS2 data

RGS1 and RGS2 data can be merged into a single "fluxed" spectrum, in units of photons cm^{-2} s^{-1}, by means of the task *rgsfluxer*. The output data, however, can no longer be analyzed in spectral fitting codes (`XSPEC`, `SPEX`). This procedure is nevertheless useful to obtain a single spectrum, or to increase

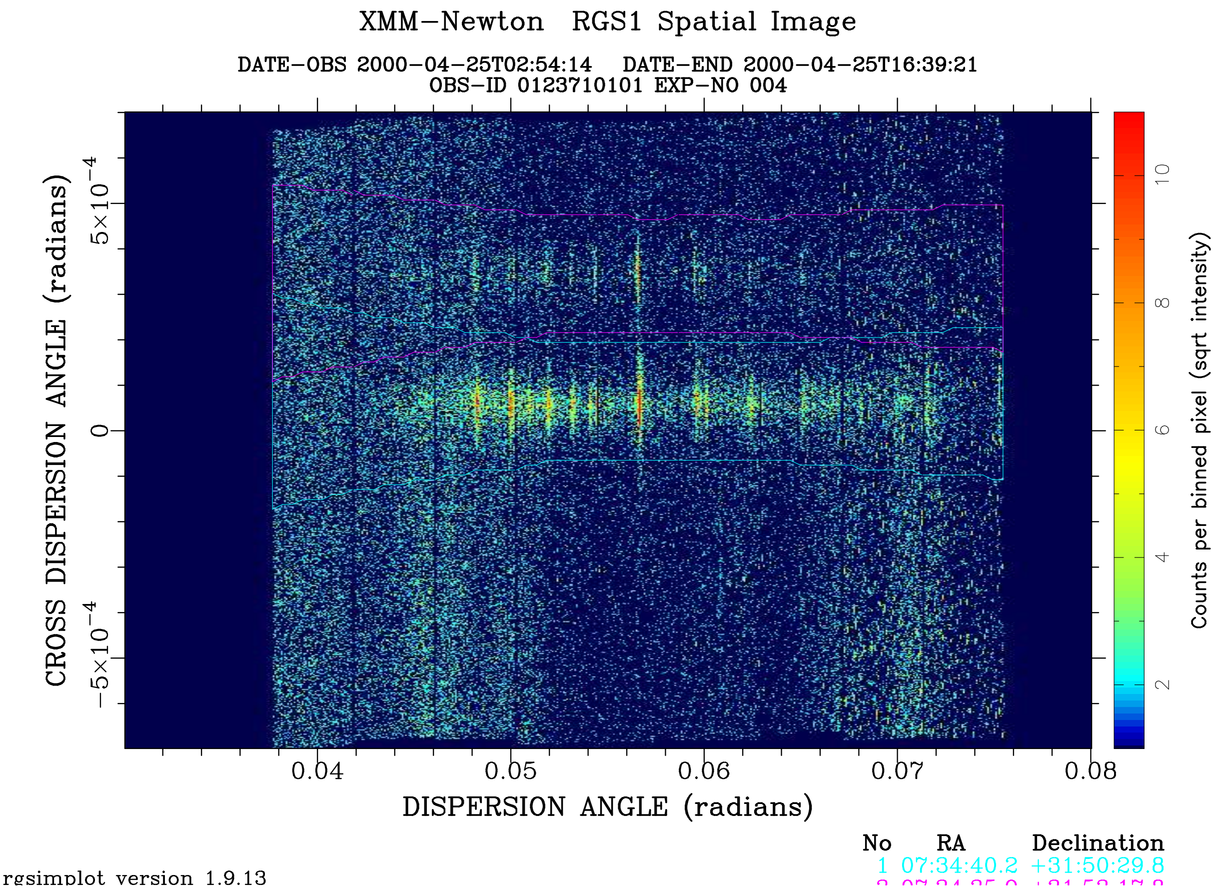

Figure 3: Output of *rgsimplot* (rev 0069, obsID 0123710101, RGS1) showing the detector image with the spatial masks for YY Gem and Castor overlaid. Note the overlap of the masks at short (small dispersion angle) and long (large dispersion angle) wavelengths for the default `xpsfincl`=90 value.

the signal-to-noise ratio to detect faint spectral features. At the expense of spectral resolution, it is also possible to merge spectra from different grating orders. The inputs of *rgsfluxer* need to come in pairs, relating a spectral file to its corresponding response matrix. Note that the "latest" SAS already provides the possibility to create a fluxed spectrum with *rgsproc*; however, the default energy resolution of the response matrix (`rmfbins`=250) is too crude. We again remind the user that fluxed spectra are not intended for quantitative analysis and that they are strictly a qualitative summary of the data.

```
SAS 5.2: rgsfluxer file='rgs12o1src1.dat' format='ascii'                        \
  pha='0232_0134720101_R1S00700_net1o1.pha 0232_0134720101_R2S00800_net1o1.pha' \
  rmf='r1o1src1.rmf r2o1src1.rmf' withaltnan=T nan=0

latest:  rgsfluxer file='rgs12o1src1.dat' format='ascii'                        \
  pha='P0134720101R1S007SRSPEC1001.FIT P0134720101R2S008SRSPEC1001.FIT'         \
  rmf='r1o1src1.rmf r2o1src1.rmf' withaltnan=T nan=0
```

References

[1] M. Audard, E. Behar, and M. Güdel et al. The XMM-Newton view of stellar coronae: High-resolution X-ray spectroscopy of Capella. Astron. Astrophys., 365:L329, 2001.

[2] J.W. den Herder, A.C. Brinkman, and S.M. Kahn et al. The Reflection Grating Spectrometer on board XMM-Newton. Astron. Astrophys., 365:L7, 2001.

[3] M. Güdel, M. Audard, and H. Magee et al. The XMM-Newton view of stellar coronae: Coronal structure in the Castor X-ray triplet. Astron. Astrophys., 365:L344, 2001.