

## JEM–X science analysis software

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**Abstract.** The science analysis of the data from JEM–X on INTEGRAL is performed through a number of levels including corrections, good time selection, imaging and source finding, spectrum and light-curve extraction. These levels consist of individual executables and the running of the complete analysis is controlled by a script where parameters for detailed settings are introduced. The end products are FITS files with a format compatible with standard analysis packages such as XSPEC.

**Key words.** software – X-ray data analysis – INTEGRAL satellite – JEM–X

### 1. Introduction

JEM–X (Joint European Monitor for X rays) is the X-ray monitor onboard INTEGRAL (Lund et al. 2003). Its primary purpose is to extend the energy coverage for the targets observed by INTEGRAL's prime instruments, IBIS (the Imager onBoard the INTEGRAL Satellite) (Ubertini et al. 2003) and SPI (the Spectrometer aboard INTEGRAL) (Vedrenne et al. 2003). The observations are composed of a number of science windows that typically are the periods of stable pointing with durations from 1800 s to 3600 s. These pointings are organized in a dither pattern around the prime target to enhance the imaging capability of SPI.

The standard data analysis is done at the INTEGRAL Science Data Centre (ISDC) at Versoix, Switzerland (Courvoisier et al. 2003). The data is taken through a series of steps in pipeline processes. The most comprehensive description of the pipelines and the executables can be found in Oxborrow et al. (2002). At present the JEM–X data analysis is done for each science window individually. Analysis of entire dither patterns will be added later on.

The first major steps as part of ISDC's technical processing are the preprocessing unpacking the telemetry format into FITS format and calculation of event onboard times in a format shared by all instruments.

Subsequently, the data are analysed by the Quick-Look and Standard Analysis pipelines which both use the same set of instrument specific software tools but with different parameter choices and range of analysis steps. Finally the data can be

analysed offline with the full range of tools. The following sections describe the analysis steps that are presented in a diagram in Fig. 1. The acronyms for the analysis levels are given both in this figure and in the headline of each section.

JEM–X can operate in imaging and non-imaging modes and the selection of analysis levels depends on this. In almost all observation situations the choice of an imaging mode is most appropriate (Lund et al. 2003).

### 2. COR: Corrections for instrumental effects

Two programs handle the energy conversion, position determination and corrections to the raw event data: `j_cor_gain` and `j_cor_position`. The first of these converts the raw Pulse Height Amplitude (PHA) values of each event from the telemetry values (256 bins covering 4096 onboard ADC channels in a non-linear fashion reflecting the energy resolution of the instruments) to Pulse Invariant (PI) values (256 bins covering 0–80 keV non-linearly). Time variations in the instrument gain are derived using the onboard radioactive calibration sources by first fitting gaussian lineshapes to the <sup>109</sup>Cd and <sup>55</sup>Fe calibration spectra. Spatial variations in gain are corrected using a table of pre-flight calibration data and a table of secondary corrections determined by offline analysis of flight data. The gain conversion program also flags all events that have poor time correlation, poor gain determination, or other deficiencies.

The position determination program uses a lookup table to find the mapping between telemetry raw *X* and *Y* co-ordinates and absolute positions measured from the centre of the detector in millimeters. This program uses an image of the detector

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showing inactive areas outside the microstrip plate, hotspots, dead anode strips and calibration spectra overspill areas, to flag every event according to the behaviour of the detector at the detection position. Events are also flagged for having a poor position determination.

Programs further down the pipeline can choose to ignore events flagged for a problem that may affect the program's output and keep those which may be less than ideal, but will not adversely affect the output.

### 3. GTI: Good-Time interval calculation

Good-Time intervals are calculated separately for: housekeeping parameters within given limits, stable attitude and data gaps. In addition, users can provide their own choice of good or bad time intervals. All these are then merged into a single GTI table which is used by the analysis tools in the subsequent analysis steps.

### 4. DEAD: Deadtime history calculation

In the pipeline processing the instrument deadtime is determined from the instrument housekeeping data. This limits the time resolution to 8 s – the housekeeping cycle time. In the off-line analysis the possibility exist to elaborate deadtime corrections with finer resolution.

Each event producing a hardware trigger on-board requires a certain processing time. This time varies from a minimum of  $16\mu\text{s}$  for events rejected by the grey filter mechanism to  $179\mu\text{s}$  for good events which pass successfully the entire on-board analysis chain. A number of intermediate cases exist, and their relative frequencies is available through the information in the housekeeping packet (see also Brandt et al. 2003).

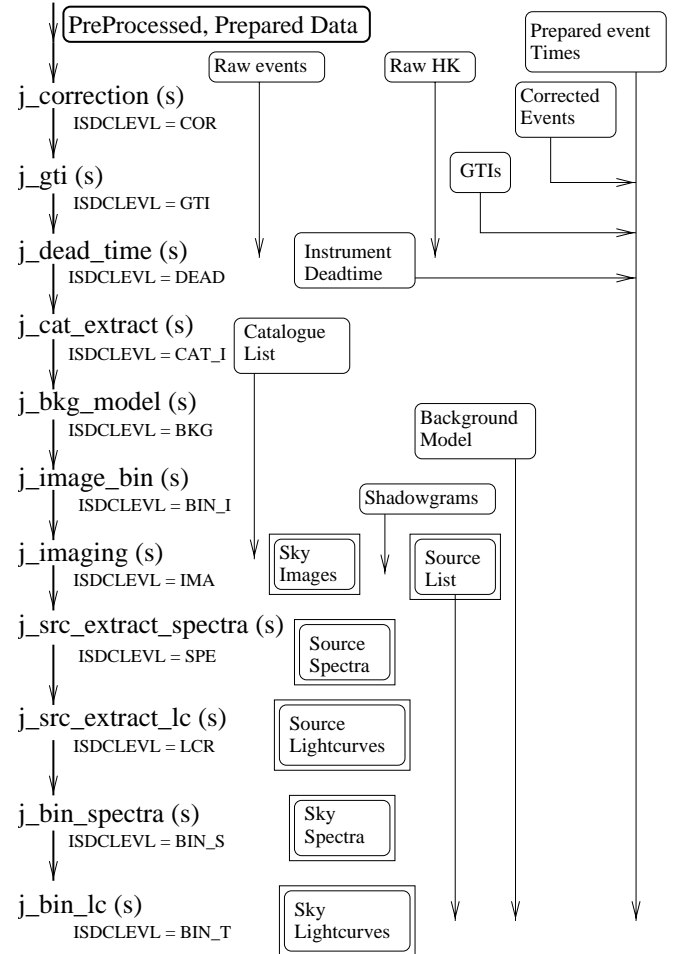
### 5. CAT\_I: Catalog source selection for imaging

A list of sources in the FOV is extracted from a reference catalog maintained by ISDC. Currently it includes around 1500 sources. This serves for comparison either in the automatic checks of Quick-Look Analysis or offline by the user. Users can also supply personal catalogs and mark the sources for which the analysis software is forced to derive fluxes even if they are not detected by the source finding algorithm.

### 6. BKG: Background model selection and derivation

The background models for JEM–X observations are determined for two background components, *diffuse background* and *instrument background*. The latter includes the particle background. The goal is to obtain good estimates of both these components at any time for any position and energy channel. The determination includes first the selection of most suitable normalised background model for each of the above components, and then scaling of these models to fit the selected data.

The *selection* is made from separate background source catalogues, which have been generated externally using background simulations and blank field observations



**Fig. 1.** Overview of JEM–X Scientific Analysis Pipeline: Processing levels are shown at the left in the order in which each is performed. To the right of these are the basic input and output data for each level. The arrows from each data box indicates the last level in which a particular type of data is used. Data in double boxes are final data products of the analysis.

(Huovelin et al. 2003). In the catalogues, there are models for various spatial and spectral distributions of background. The selection of *diffuse background model* is made according to the sky coordinates of the observation, and the *instrument background model* is selected according to orbital phase, attitude parameters, and radiation monitor level during the observation.

The scaling is made using scaling factors, with the purpose of fitting the equally normalised background models obtained with the above selection process to the associated set of observations. The parameters for the scaling factor determination are the same as those of the background models. The scaling factors are defined for each 8 s interval in OBT format, thus allowing the modelling of even rapidly variable instrumental background.

The final result of the background determination process is an estimate of the diffuse and instrument background counts for the specified time interval in each spectral channel and spatial coordinate on the detector. The specific files supplied include

1. maps of background strength for diffuse and instrument background;

2. maps of background spectral shape as a function of position; and
3. a time history of flux variation.

The consistency of the result is controlled within the software. Fine tuning will be possible with an interactive background software tool which is to be finalised soon.

The use of a background model is not enforced although there is a default pipeline for background modelling. If the user chooses to reduce the background from his/her JEM–X data, it can be done using either the default background model, or a model created with the interactive background software, where model parameters can be adjusted with full flexibility.

### 7. BIN\_I: Binning of event data into shadowgrams for imaging

A shadowgram is a 2D histogram of the distribution of counts on the detector. For the basic image reconstruction algorithm (see next section) the pixels of the shadowgram are organized as the hexagonal cells of the coded mask (Lund et al. 2003). This is done in a skew coordinate system so that the correlation with the mask is straightforward. The binning process introduces corrections for deadtime and grey filter value for each event since these corrections can vary rapidly with time. The time and energy interval can be selected by means of parameters.

The pixel size of the detector is 1 mm in both directions which is finer than the mask cell size (3.3 mm). A shadowgram with full resolution and normal cartesian coordinates can also be produced.

### 8. IMA: Image reconstruction

This step consists of image reconstruction, source finding, source flux determination and correction.

The current image reconstruction algorithm is a standard correlation of the shadowgram with the coded mask pattern. The effect of the collimator is disregarded.

The source finding consists of a blind search in the reconstructed image. Each source candidate is characterized by a detection significance and a limit for acceptance can be defined as a parameter. The accepted sources are organized in a list with a flux value derived from the peak size in the image for the same energy intervals as given for the shadowgram binning.

Finally the image and flux values can be corrected for the vignetting.

Spurious sources may appear in particular at the rim of the image where the sensitivity is very low but the noise level is high.

**Future developments:** A refined image reconstruction taking into account the presence of the collimator is underway.

### 9. SPE: Spectra and response extraction for individual sources

The source data extraction is based on an algorithm, which is similar to photon tagging (Fenimore 1986). Each detected

photon is backprojected through the mask and its contribution to the source and background flux estimates for the particular source is computed. The spectrum is built up by the net contribution from all detected photons.

The computational efficiency compared to image deconvolution is high because few sources are involved and for JEM–X the number of resolution elements (mask and detector) is large while the event rate is still modest. Furthermore, the execution time depends only weakly on the number of time and spectrum bins.

Any flat background component is automatically subtracted by the analysis procedure.

A single response matrix, RMF (Redistribution Matrix file), is used for all sources. The RMF is part of the calibration data and may evolve with time. When extracting source spectra from a science window an Ancillary Response Function, ARF, is produced for each source. The ARF contains the effective area as function of energy, taking various efficiency factors, e.g. vignetting, into account. All energy redistribution information is kept in the RMF. The data formats are compatible with XSPEC.

### 10. LCR: Lightcurve extraction for individual sources

The algorithm used for source light curve extraction is almost identical to that for spectral extraction. The essential differences are in the time-energy bins and the data format used and that no response files are written.

### 11. BIN\_S: Binning of detector spectra

For the JEM–X datamodes without position information spectra of the whole detector area can be generated. Time and phase resolved binning is possible. The binned fluxes are corrected for exposure, grey filter and deadtime effects. If background model data (see section BKG) is available it is binned accordingly. If the datamode is imaging then it is possible to bin a subset of events, e.g. only part of the detector area via a selection parameter.

### 12. BIN\_T: Binning of detector lightcurves

Similarly to the detector spectra (BIN\_S above), energy resolved light curves can be generated from the whole detector area. Again with a provision for phase resolved binning and including folding of background model data.

### 13. Instrument characteristic files

A number of files describing the properties of the instrument are supplied to ISDC by the instrument team. At ISDC they are organized in the so-called `ic_tree` where the times of validity are indicated. Several of the properties change with time and it is ensured that the appropriate IC file for the time frame of the data is selected.

### 13.1. Instrument model

The “JMXi-IMOD-GRP” contains information for the event corrections such as position and spatial gain correction. Material properties and binning information is also found here as well as a map of the quality of the individual detector pixels.

### 13.2. Redistribution matrix

The “JMXi-RMF-GRP” holds the redistribution matrix (RMF) and the auxiliary (on-axis) response function (ARF) in the OGIP format.

### 13.3. Background models

The background associated files in the data are identified by extension -DBG for diffuse background, and -BKG for instrument background. There are two different types of background files for each of the two background components in the external background source catalogue. The types in the catalogue are associated with different *spatial* and *spectral* distributions of background, and each type can be selected independently to allow maximum flexibility for the modelling. The mapping of spectral models is handled by index tables providing the identification of a spectral model for each position on JEM-X. The models are applied to shadowgrams, not reconstructed images. At present the model catalogue is under evaluation, and details of the modelling can be found in Huovelin et al. (2003).

## 14. IBAS: A JEM-X element for the INTEGRAL burst alert system

A JEM-X element for the IBAS Burst Alert System is in preparation. In addition to the improved positioning accuracy offered by JEM-X it will also open the opportunity to search for very soft bursts, “X-ray flashes”.

The source detection algorithms developed for IBAS differs from those described in Sect. 8 in several respects, of which the following two are of particular importance:

- In the IBAS algorithm the collimator shadowing is considered in the image reconstruction. This improves the sensitivity at the edge of the field of view.

- The uneven background which is a major source of problems for all image reconstruction programs is introduced as a separate model component in the fit to the observed shadowgrams.

When it was realized, after the launch of INTEGRAL, that the instrument background was considerably more structured than expected the importance of taking this into account also for the standard ISDC pipelines became apparent. For this reason the emphasis in the IBAS work moved from finishing the IBAS element proper to transferring the algorithms of JEM-X IBAS software to the JEM-X ISDC pipeline. The preparation for this transfer are now completed, and the work on the missing IBAS elements will now be resumed. It is expected that the JEM-X IBAS element can be integrated in September 2003.

## 15. Conclusions

The basic pipeline processing runs smoothly as well as the standard scientific analysis. The verification of the results is ongoing but so far the results are grossly correct. The current developments are focussed on better imaging, better modelling of the background, and improved source spectrum/lightcurve extraction.

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