

Data analysis software for the IBIS/PICsIT high energy detector on INTEGRAL

Luigi Foschini, John B. Stephen, Fulvio Gianotti, Guido Di Cocco, and Giuseppe Malaguti

Istituto di Astrofisica Spaziale e Fisica Cosmica (IASF) del CNR
Sezione di Bologna (formerly iTesRE) - Italy

ABSTRACT

The INTEGRAL gamma-ray observatory is due to be launched in October 2002 on a Proton rocket from the Russian base in Baikonur in Kazakhstan. Its scientific payload contains two main instruments on board, one dedicated to spectrometry (SPI) and with moderate imaging capabilities, and the other (IBIS) designated to produce high angular resolution images with moderate energy resolution, in addition to X-ray and Optical monitors. The IBIS telescope itself consists of two main subsystems: a low energy (15 keV – 1 MeV) detector (ISGRI) and a plane (PICsIT) working at higher energies (170 keV – 10 MeV). Both these instruments use the same coded aperture mask in order to create images of the sky over the entire energy range with a resolution of 12 arcminutes and point source location accuracy down to tens of arcseconds for the strongest sources. The data from the satellite will be transmitted to the INTEGRAL Science Data Centre (ISDC) located near Geneva for initial processing and distribution of the analysis results. The quantity of data is large, and each observation will typically consist of many individual pointings around the target, which will then be summed together. This allows a reduction of systematic effects in the creation of the spectral imaging images. Herein we describe the data structure of the PICsIT instrument from raw low-level data through to the high-level scientific products, indicating how the data sets are used to obtain images and spectra for celestial gamma-ray sources.

Keywords: INTEGRAL, PICsIT, Data Analysis, Instrument Specific Software

1. INTRODUCTION

The scientific objectives of the INTEGRAL satellite are the imaging and spectroscopy of the sky in the X and gamma energy bands. The IBIS^{1*} telescope (15 keV – 10 MeV) is the imager of the satellite and consists of two detectors, ISGRI and PICsIT,² the former operating below about 1 MeV, while the latter functions at higher energies (170 keV – 10 MeV). See Table 1 for a quick look at the main characteristics of IBIS/PICsIT.

To allow fine positioning of detected sources, a coded mask is situated at about 3.2 m above the PICsIT layer, so as to provide an angular resolution of 12 arcmin. The purpose of the mask is to stop some of the incoming photons, thereby producing shadows on the detector (shadowgrams are therefore the number of photons recorded at each pixel position). To obtain the original image of the sky region, it is necessary to perform a deconvolution of the shadowgram with the mask transfer function. See Caroli et al.³ for further details on coded masks.

In the following sections, the Instrument Specific Software for IBIS/PICsIT is described, including the data structure and the scientific analysis. Some examples of shadowgrams and spectra from the INTEGRAL End-to-End (E2E) Tests (19 January 2001) and payload calibrations are shown.

Further author information: (Send correspondence to J.B.S.)

J.B.S.: E-mail: stephen@bo.iasf.cnr.it, Telephone: +39 051 6398731

*See also <http://ibis.ias.rm.cnr.it/Menu/HomeNet.htm>

Table 1. Short identity card for IBIS/PICsIT.

Energy range	170 keV – 10 MeV
Pixels	4096 (64 × 64) organized in 16 semimodules
Active area	≈ 2856 cm ²
Field of View	9° × 9° (fully coded) 19° × 19° (half coded) 29° × 29° (zero response)
Angular Resolution	12'
Time Resolution	≈ 1 ms
Point Source Location accuracy	1' (20σ)
Energy Resolution	12% @ 662 keV 9% @ 1 MeV
Sensitivity (@ 1 MeV)	1 – 2 × 10 ⁻⁷ ph cm ⁻² s ⁻¹ keV ⁻¹

2. GENERAL OVERVIEW

2.1. The IBIS/PICsIT Specific Software

The software for IBIS/PICsIT is composed of several parts: the on board software (Hardware Event Pre-processor of IBIS HEPI, Instrument Application Software IASW, Data Processing Electronics DPE) to preprocess the data and to prepare telemetry packets for the transmission to the ground (integration of events, multiple events reconstruction, etc.); the *Instrument Specific Software* (ISSW, that is the subject of the present paper); the Ground Support Equipment (GSE) software; other software for modelling, MOC, ISDC, etc.

The ISSW works on the data structure created by the preprocessing of the INTEGRAL Science Data Centre (ISDC, Geneva) and includes the Operating System Monitoring (OSM), the Automatic Calibration Analysis (ACA), and the Standard Scientific Analysis. Once the telemetry is received on the ground (Mission Operation Centre, MOC), it is sent to the ISDC and preprocessed. This creates the INTEGRAL data structure, composed of raw (RAW) and prepared data (PRP). The latter consists of the addition of the on board time, to the raw data. The ISSW starts working at these levels (RAW and PRP). The OSM and ACA are part of the V1 software, while the Standard Analysis is also called V2.

The ISSW is developed by the Instrument Teams, with the help of the ISDC, which provides some specific libraries to manage the huge data structure of INTEGRAL (DAL). The ISSW for PICsIT is developed in C on Linux, but it is compatible also with Sun/Solaris. In addition to the ISDC specific libraries, it makes use of standard astronomical libraries (FITS⁴ and WCS[†]) and format (OGIP[‡]). The software will be available to the astronomical community through the ISDC[§].

The expected amount of raw data is very high: for a 100 ks observation, PICsIT alone will produce between 1.5 GB and 19 GB of data, in the best and worst case respectively, depending on the in-orbit background. The latter is a very important unknown, able to influence the whole activity of the INTEGRAL satellite. Only when the instrument is in the space environment, will it be possible to perform an accurate measurement of the background.

2.2. IBIS/PICsIT modes of operation

Because of the limited available telemetry of the INTEGRAL satellite, three modes of operation had to be created and implemented for PICsIT in order to optimize data handling and transmission. These modes are: standard, photon-by-photon, and polarimetry. The *Standard mode* is composed of two submodes: *spectral*

[†]<http://www.atnf.csiro.au/people/mcalabre/WCS.htm>

[‡]http://heasarc.gsfc.nasa.gov/docs/heasarc/ofwg/ofwg_recomm.html

[§]<http://isdc.unige.ch/>

imaging (SPI) and *spectral timing* (SPT). Events are integrated on-board on a characteristic time scale of 30 minutes, producing histograms. In this way, the required telemetry is fixed and does not depend upon the (unknown) background count rate.

In spectral imaging, histograms are optimized for spatial resolution, so in the integration we lose the timing information and the energy resolution is reduced, from 1024 to 256 channels. The histograms are cubes of data with dimensions $256 \times 64 \times 64$ (energy channels \times pixels \times pixels). Two types of histograms are accumulated simultaneously, one for single events, and one for multiple events.

In spectral timing, the purpose is to keep the temporal resolution, so in the integration we lose the position and the energy resolution. The histograms are divided by default in two programmable energy bands with 1 ms time resolution. The energy bands can be switched up to 8 by using a telecommand, and with decreasing time resolution (down to 500 ms) to keep the same telemetry allocation.

If the background count rate is low enough, PICsIT can be switched to *photon-by-photon* mode (PPM). In this case, each event is transmitted with its characteristic informations: energy channel, at the highest resolution of 1024 channels, pixel position (Y, Z), and time lag between events. The photon-by-photon mode is used also during slews between dithering pointings, even though the standard mode is turned on.

In all operation modes, single events and multiple events are treated separately and the primary energy and incident pixel of multiple events are reconstructed on board.

The last mode of operation of the IBIS/PICsIT instrument is the *polarimetry* mode (POL), that will be not available during the first year of operation. Indeed, it requires a deep in flight calibration and analysis with real data, to understand the efficiency and the reliability of this mode. We refer to the paper by J.B. Stephen et al.⁵ for further details.

3. THE INSTRUMENT SPECIFIC SOFTWARE V1 (ISSW-V1)

3.1. V1: The Operating Status Monitoring (OSM)

OSM is composed of three executables (four, including POL), one for each mode/submode (SPI, SPT, PPM). The purpose of the OSM is to perform health monitoring of PICsIT. This software works offline and therefore it is useful only for an *a posteriori* evaluation of the instrument performances. It is not part of the Interactive OSM, developed by the ISDC for an immediate check.

The data products of OSM are:

- shadowgrams in three energy bands (SPI, PPM);
- energy spectra for each of the 16 semimodules (SPI, PPM);
- lightcurves for the whole detector (SPT, PPM);
- miscellaneous data: good pixels, counting rate statistics (mean value, standard deviation, maximum and minimum counts) for PICsIT in all modes.

3.2. V1: The Automatic Calibration Analysis (ACA)

ACA is a single executable that runs once every orbit of INTEGRAL and checks the temperatures of PICsIT semimodules from housekeeping data. If values are too much different from reference values, the executable calculates the changes in the pixels gain and offset and updates the tables. The relationship between temperature and gain and offset for each single pixel has been calculated using calibration data.

3.3. V1: The calculation of deadtimes

Even though this executable is part of V1, it is also used in the standard analysis (V2). It reads livetime counters, ratemeters, and VETO strobe from housekeeping data and calculates the deadtime for each semimodule.

4. THE STANDARD SCIENTIFIC ANALYSIS (ISSW-V2)

The Standard analysis is created to produce for the final user (guest observer) a set of scientific data, which are: images, spectra, and lightcurves. A quick summary of the pipelines for V2, according to the IBIS/PICsIT mode of operation, is available in Tables 2 and 3. In the following sections a short description of the intermediate tasks is shown.

Table 2. Summary of pipeline of IBIS/PICsIT V2 (Standard Mode)

Step	Images SPI	Spectra SPI	Lightcurves SPT
1	G&O correction	G&O correction	G&O correction
2	Build shadowgrams (energy bins)	Build shadowgrams (energy bins)	Rebin timing data and extract FOV lightcurve
3	Background correction	Background correction	
4	Deconvolution	Single source spectra extraction	

Table 3. Summary of pipeline of IBIS/PICsIT V2 (PPM Mode)

Step	Images	Spectra	Lightcurves
1	G&O correction	G&O correction	G&O correction
2	Build shadowgrams (energy bins)	Build shadowgrams (energy bins)	Build shadowgrams (time bins)
3	Background correction	Background correction	Background correction
4	Deconvolution	Single source spectra extraction	Single source lightcurve extraction

4.1. V2: Gain and offset correction

The first step in the scientific analysis is to correct raw data for the pixel gain and offset, and to calculate the conversion from channel to energy. This is performed by three executables, one for each mode/submode (SPI, SPT, PPM), which receive in input the gain and offset table, updated by ACA every orbit.

However, although this correction is more or less easy in photon-by-photon mode, it is not straightforward in standard mode because data are integrated in histograms. In this case, a redistribution of photons is performed.

The correction is not applied to multiple events because they are already partially corrected onboard by HEPI during the reconstruction of the event. Further corrections are not possible because of the loss of some spatial information (cf also Malaguti et al.²).

4.2. V2: Shadowgram building

The following step is to build shadowgrams: in standard mode, this consists of the rebinning of the histograms, while in photon-by-photon, the events are accumulated on the plane according to the selected energy bands. To do this task there are two executables: one for the spectral imaging submode and the other for PPM. The latter is also able to build shadowgrams according to time bin (for lightcurve extraction).

At this step, the corrections for deadtimes and faulty pixels are included. Fig. 1 shows an example of shadowgram built from single events. Boundary effects of modules are clearly visible as excess in counts.

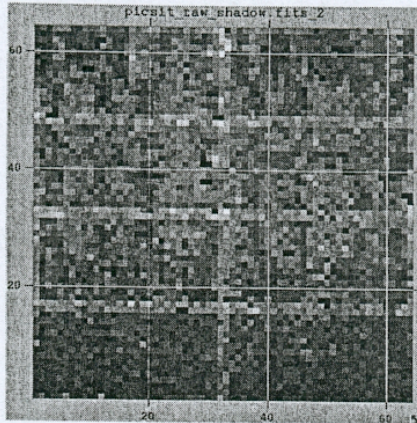


Figure 1. Example of shadowgrams built from data of INTEGRAL E2E Tests (19 Jan 2002). The black pixels are off.

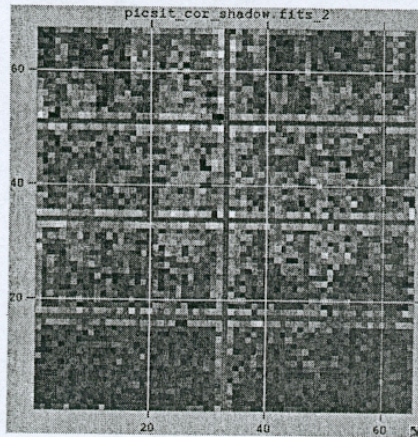


Figure 2. Example of expanded shadowgrams built from data of INTEGRAL E2E Tests (19 Jan 2002). The gaps between the modules filled with the average value of counts are clearly visible.

4.3. V2: Background correction

Once the shadowgrams are built, before performing the deconvolution for images, spectra, or lightcurves, it is necessary to apply some corrections to take into account the background, the non-uniformities of the detector (e.g., close to the gaps between modules), and the second order corrections to take into account residual aberrations due to highly time variable structures (see Bouchet et al.⁶ for the same concepts applied to the SIGMA telescope). In addition, the gaps between modules should be filled or tagged for null weight in the following deconvolution. To do this task, the shadowgrams are then expanded from dimension 64×64 to 65×67 . For an example of expanded shadowgram, see Fig. 2.

4.4. V2: Images deconvolution

IBIS detection planes are “shadowed” by the coded mask (from which the word “shadowgram” to refer to the array of counts along the detector plane). To reconstruct the sky image is then necessary to perform a mathematical operation (deconvolution, cf Caroli et al.,³ Goldwurm et al.⁷ for more details). Specifically, the PICsIT software performs a weighted cross-correlation. The expanded shadowgram, which is the output of the previous task, is cross-correlated with a specific decoding pattern, which in turn is weighted according to the illuminated fraction of the mask with two other specific arrays (see Fig. 3).

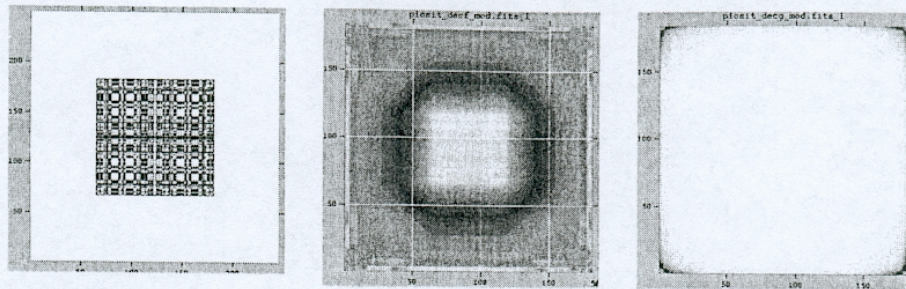


Figure 3. Arrays used for the deconvolution: (A, left) decoding pattern; (B, centre) weighting factor F; (C, left) weighting factor G

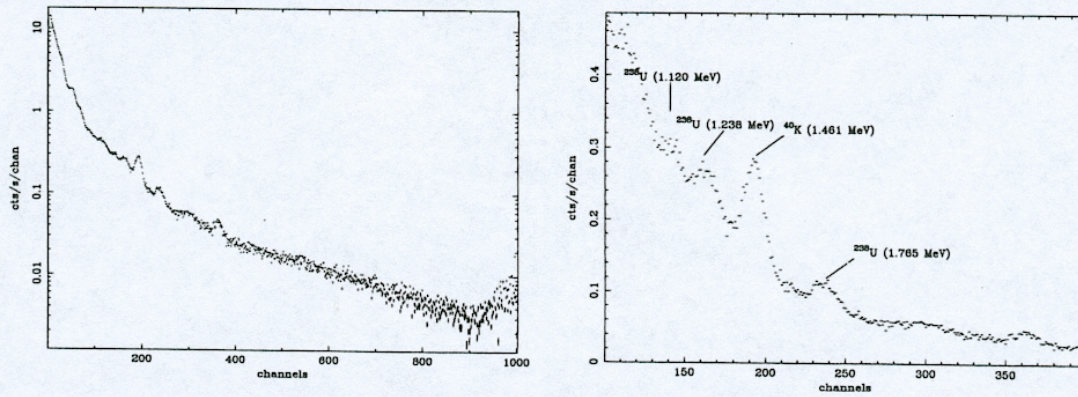


Figure 4. PICsIT background spectrum, taken during the Payload Calibrations in PPM (January–February 2002). Left, the full spectrum. Right, a zoom of the image, with some spectral lines recognized.

The raw image contains some byproducts of the deconvolution (ghosts, which are fake sources) and therefore a cleaning algorithm is needed. Then, once the true sources are identified, the coordinates and fluxes are calculated.

4.5. V2: Spectra extraction

The coded mask technique implies the use of non-conventional methods for the extraction of the spectra. In fact, the photons arriving from a source in the sky are spread all over the detector and it is possible to extract the spectrum for all the sources in the FOV.

This executable extracts all the known sources in the selected FOV and calculates how each source illuminates the mask. Then it sums all the models of illumination and fit the results to the data (shadowgram), checking with the χ^2 test.

4.6. V2: Lightcurve extraction

The extraction of the lightcurve for each source is in principle the same as for extracting the spectrum. The only difference is that the shadowgrams are now rebinned in time, instead of energy. This is if PICsIT is in PPM mode.

If PICsIT is in standard mode, this is not possible because the presence of the histograms. In this case, it is only possible to extract a cumulative lightcurve for the whole FOV from the spectral timing data. The method of using SPT data is useful if there is a very bright source in the FOV or when there are sources with known timing behaviour.

5. FINAL REMARKS

The conceptual design of the Instrument Specific Software of PICsIT, the high-energy detector of the IBIS telescope on board the INTEGRAL satellite, has been presented. The ISSW includes the operating status monitoring, the automatic calibration analysis, and the standard scientific analysis. Some examples of shadowgrams from the E2E tests of January 2002 and spectra from the Payload Calibrations have been presented.

ACKNOWLEDGMENTS

We acknowledge the Italian Space Agency (ASI) for partially supporting this work.

REFERENCES

1. P. Ubertini et al., in *Proc. V Compton Symposium*, AIP Conference Proceedings **510**, p.684-688, 2000
2. G. Malaguti et al., *Proceedings SPIE* **4497**, p. 199-210, 2002.
3. E. Caroli et al., *Space Science Reviews* **45**, p. 349-403, 1987.
4. Hanisch et al., *Astronomy & Astrophysics* **376**, p. 359-380, 2001.
5. J.B. Stephen et al., in *Gamma 2001: Gamma-ray Astrophysics 2001*, AIP Conference Proceedings **587**, p. 816-820, 2001.
6. Bouchet L. et al., *The Astrophysical Journal* **548**, p. 990-1009, 2001.
7. Goldwurm A. et al., *Proceedings IV INTEGRAL Workshop - Exploring the Gamma-ray Universe*, ESA SP-459, p. 497-500, 2001