INTEGRAL/SPI DATA ANALYSIS

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I give a brief introduction to the analysis tools developed for the spectrometer SPI on INTEGRAL. For the general user the tools of most interest are point-source detection and spectral analysis, and imaging of extended emission. The main data types and analysis steps are described, illustrated with examples using simulations of typical SPI observations and the Galactic centre deep exposure survey.

1 Introduction

The SPI instrument on INTEGRAL[a] is designed to perform imaging and high-resolution spectroscopy of γ-rays with energies from 20 keV to 8 MeV. The main elements are 19 cooled high-purity germanium detectors in a hexagonal array, and a tungsten coded mask. The instrument is surrounded by an anticoincidence system based on BGO crystals, and a plastic scintillator anticoincidence shield is situated below the mask. Background reduction is provided by a pulse-shape-discrimination system. A description of SPI can be found in Mandrou et al.[1] and a review of the application of coded-mask techniques in γ-ray astronomy is given by Skinner[2].

As for all INTEGRAL instruments, the SPI analysis software will be made available to the scientific community via the INTEGRAL Science Data Centre[b] (ISDC) near Geneva. All INTEGRAL raw telemetry data will be sent in near-real-time to the ISDC where they will be preprocessed, archived and distributed to the user community. This article gives a short description of the data analysis tools which have been prepared by the SPI team for use by observers, with some examples using simulated data. It does not address the lower-level processing stages. Full details of the analysis tools will be made available in the ISDC User's Manual.

The SPI analysis software has been extensively tested on data from the SPI calibration campaign[c] at Bruyères-le-Châtel in April 2001, and shown to perform very well.

2 Observations

In flight, the SPI performance is fundamentally improved though the use of 'dithered' pointings such as the standard $10^o \times 10^o$ pattern with pointings at 2^o pitch. A typical observation duration is 10^6 sec, each individual pointing has an exposure of 30 min. The Core Program includes the Galactic Centre Deep Exposure (GCDE) which covers the inner Galactic radian with an exposure of 4 10^6 sec per year of the mission; this will allow mapping of large-scale diffuse

[a] http://astro.estec.esa.nl/SA-general/Projects/Integral
[b] http://isdc.unige.ch
[c] http://membres.lycos.fr/spitog/spi/spical.html

extended emission and a survey of inner-Galaxy sources. Details of the Core Program and Open Time are available at the INTEGRAL Science Operations Centre [d].

3 Basic input data for analysis

The source detection and imaging analyses are based on *binned events* together with datasets containing information on pointing, exposure time, dead time, etc. The other essential ingredients for analysis are the instrumental response function and a model for the instrumental background.

3.1 Calibrated and binned events

The starting point for most analysis of SPI data are the *calibrated events*, that is the photon-by-photon data with the channel-to-energy conversion applied. These are derived from the raw event data and calibration curves available at ISDC. For each event, the detector identification, energy (keV), and timing information is provided. Since a large number of γ-rays scatter in two or more adjacent detectors, such multiple events are assigned a 'virtual detector' identification, and the subsequent treatment is then formally equivalent to that for single detectors. The first step in the analysis is to bin the event data using the tool *spihist*; this produces a FITS dataset containing a binned spectrum for each detector/virtual detector, and for each instrument pointing belonging to the observation or survey. The *binned event data* is the basis for all subsequent source detection, imaging and spectroscopy.

3.2 Instrumental Response

The instrument response function (IRF) has been obtained by extensive Monte-Carlo simulations using the SPI and INTEGRAL spacecraft mass models. The simulated events are used as the basis for a factorized model of the response which can be accurately and efficiently interpolated in both direction and energy. The work has been performed by the GSFC SPI group [e]. The response has been tested against data from the calibration campaign, and the agreement is good. The IRFs are available at ISDC.

3.3 Instrumental Background Model

The instrumental background has been studied using simulations based on the SPI and INTEGRAL spacecraft mass models and the expected charged-particle environment in orbit [3]. Fundamental to the analysis methods is however the approach to determine the background in each detector from the data themselves, through the use of dithered observations. The principle is simple: as the pointing changes the characteristic signature of a source seen through the mask changes, while the background is constant. Thus the source and background signatures can be separated. Clearly, temporal variations in the background will limit this method, so that additional modelling of the time-dependence is foreseen. Using the tool *spiback* it is possible to generate templates of the temporal variation, which are then used in the source and imaging analysis.

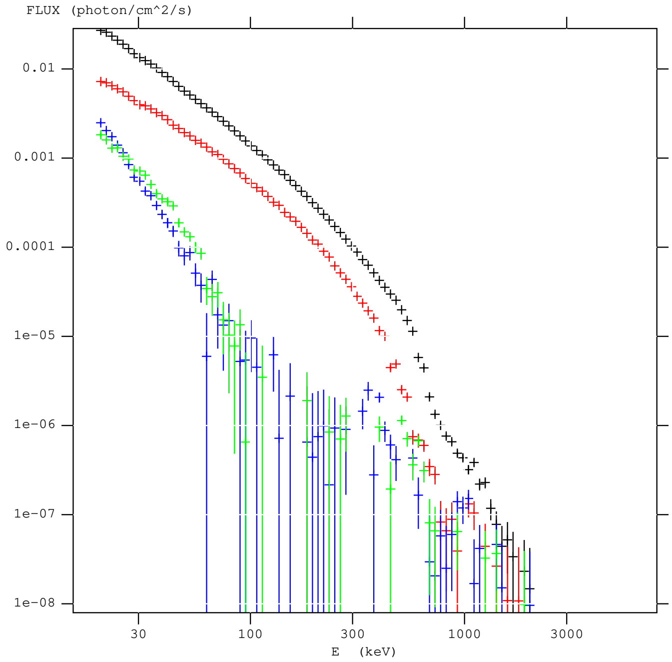

Figure 1: Simulated *spiros* spectra of 4 sources, fitted simultaneously. 10^6 sec. exposure, 25 pointing dither pattern. Courtesy of P. Connell.

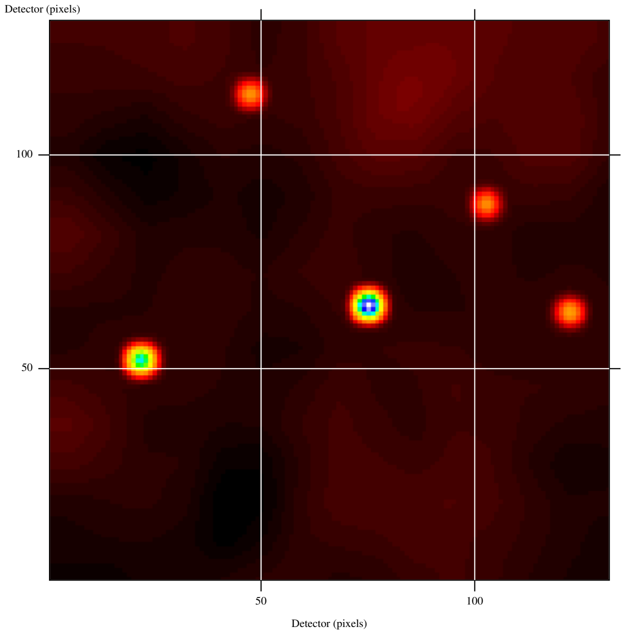

Figure 2: Simulated *spiros* map (70–150 keV) of SIGMA sources in inner Galaxy. GCDE exposure. Courtesy of P. Connell.

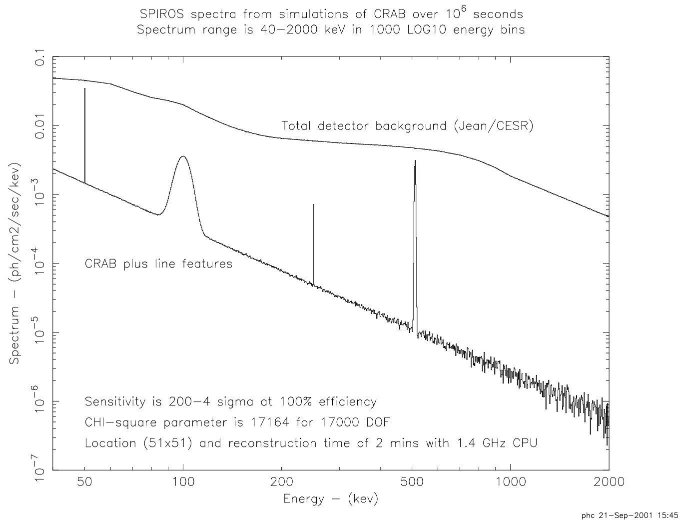

Figure 3: Simulated *spiros* spectrum of power-law source with line features. Courtesy of P. Connell.

4 Source detection and spectral extraction

The standard tool for source detection is called *spiros* [f]. Sources are first successively detected and roughly located with a correlation method, and then accurate positions and fluxes are obtained by simultaneous fitting of all sources. The background is fitted as part of the analysis using the template from *spiback*. As well as locating sources and determining their significances, *spiros* generates source spectra, and it can also be used for imaging extended emission. In addition, *spiros* output can be used as input to the spectral model-fitting package *xspec*, which is being enhanced for SPI. Fig 1 shows an example of *spiros* spectral analysis for four sources with different (continuum) spectra, for a typical exposure of 10^6 sec. Fig 2 shows a simulation of a GCDE observation of inner-Galaxy sources from the SIGMA catalogue. To illustrate the extraction of a more complex spectrum, Fig 3 shows a Crab-like source with added line features.

5 Imaging of extended emission

The *spiskymax* program is designed for imaging extended emission, both continuum and lines. It can also be used for source flux determination where the source position is known. *spiskymax* is based on the maximum-entropy 'MaxEnt classic' method [4,5] and uses the MEMSYS5 package. A feature of this approach is that is provides not just an image but also profiles with rigorous error estimates. A full description can be found in the user manual [g]. As in the *spiros* method, the background is determined simultaneously with the image. Fig 3 shows a simulated GCDE observation (4 10^6 sec) of the Galactic ridge 511 keV line; the input model is based on OSSE results [6]. Fig 4 shows the same observation imaged in the hard X-ray continuum for 200-400 keV; the input map is also based on OSSE results [7].

[d] http://astro.estec.esa.nl/Integral/isoc
[e] http://lheawww.gsfc.nasa.gov/docs/gamcosray/legr/integral/
[f] http://www.sr.bham.ac.uk/~phc/INTEGRAL/overview.html
[g] http://www.mpe.mpg.de/~aws/integral.html

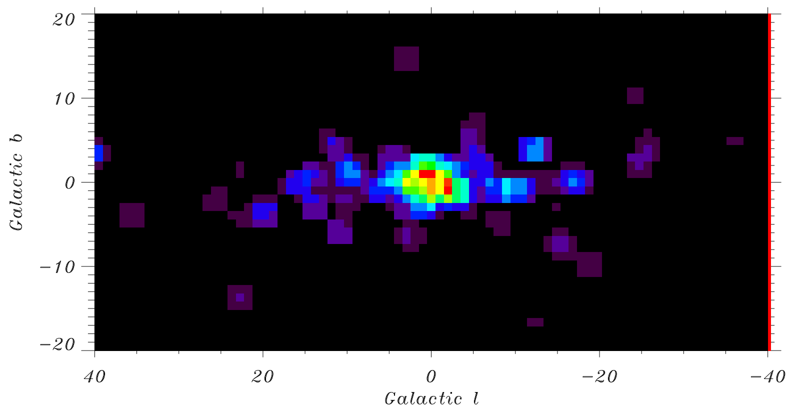

Figure 4: Simulated *spiskymax* map of 511 keV Galactic plane emission. GCDE exposure.

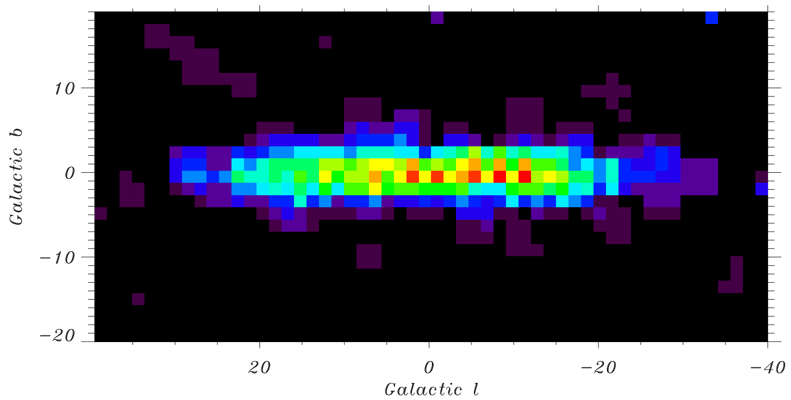

Figure 5: Simulated *spiskymax* map of 200–400 keV continuum Galactic plane emission. GCDE exposure.

6 Diffuse model fitting

Since neither *spiros* nor *spiskymax* address the problem of spatial model fitting of diffuse emission, a tool *spidiffit* was developed for this purpose. It is aimed in particular at obtaining spectra of diffuse continuum and line emission in cases where the signal is too weak to obtain spectra directly by imaging, and where plausible astrophysically-based tracer surveys are available (e.g. free-free emission surveys for ^{26}Al, HI and CO gas surveys for continuum). Fig 6 shows an example of a GCDE observation of the Galactic ^{26}Al 1809 keV line, broadened [8] in energy to a Gaussian with σ=2.0 keV, and assuming the emission is traced by free-free emission [9]. The line shape is recovered satisfactorily.

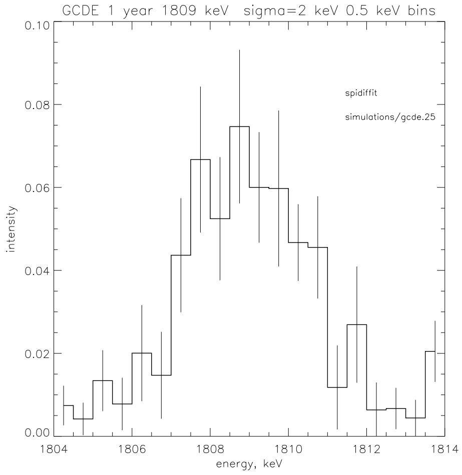

Figure 6: Simulated *spidiffit* spectrum of broadened ^{26}Al 1809 keV Galactic plane emission. GCDE exposure.

References

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