PROCEEDINGS OF SCIENCE

INTEGRAL IBIS/ISGRI energy calibration in OSA 10

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We present the new energy calibration of the ISGRI detector onboard *INTEGRAL*, that has been implemented in the Offline Scientific Analysis (OSA) version 10. With the previous OSA 9 version, a clear departure from stability of both W and ^{22}Na background lines was observed after MJD$\sim$54307 (revolution $\sim$583). To solve this problem, the energy correction in OSA 10 uses: 1) a new description for the gain depending on the time and the pulse rise time, 2) an improved temperature correction per module, and 3) a varying shape of the low threshold, corrected for the change in energy resolution. With OSA 10, both background lines show a remarkably stable behavior with a relative energy variation below 1% around the nominal position ($>$6% in OSA 9), and the energy reconstruction at low energies is more stable compared to previous OSA versions. We extracted Crab light curves with ISGRI in different energy bands using all available data since the beginning of the mission, and found a very good agreement with the currently operational hard X-ray instruments *Swift*/BAT and *Fermi*/GBM.

An INTEGRAL view of the high-energy sky (the first 10 years)" 9th INTEGRAL Workshop and celebration of the 10th anniversary of the launch,
October 15-19, 2012
Bibliotheque Nationale de France, Paris, France

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PoS(INTEGRAL 2012)142

1. IBIS/ISGRI energy calibration

1.1 Energy calibration with OSA 9

ISGRI [1] is the low energy detector of the IBIS imager [2] on-board *INTEGRAL* [3], and is made of 128x128 cadmium telluride (CdTe) pixels grouped in 8 Modular Detector Units (MDU). The scientific data analysis is performed with the Offline Scientific Analysis software package OSA, delivered by the ISDC[1]. The ISGRI spectral gain decreases with time. In the OSA 9 version, the description of the gain drift was based on the Radiation Environment Monitor (IREM) counters [4] integrated over time, to take into account the solar flares. The gain is followed using the radioactive sodium (^{22}Na) and tungsten (W) fluorescence lines located at 511 and 58.8297 keV[2], respectively. As shown in Fig. 1, the energy reconstruction used in OSA 9 is not valid since IJD[3]$\sim$2763 (revolution number $\sim$583). The position of the background fluorescence lines shows a gradual increase with time.

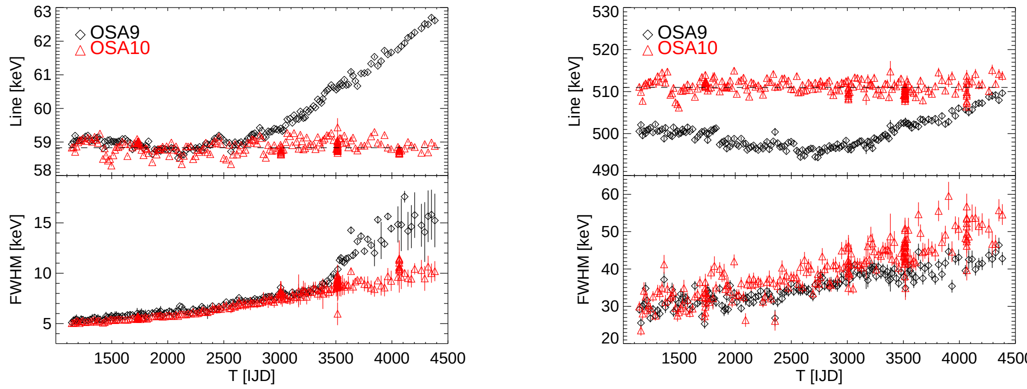

Figure 1: *Left:* evolution of the W fluorescence line position (top) and FWHM (bottom) obtained with OSA 9 (black) and OSA 10 (red). *Right:* Evolution of the ^{22}Na line position (top) and FWHM (bottom) obtained with OSA 9 (black) and OSA 10 (red). The dashed horizontal lines in the upper panels represent the nominal positions of the W and ^{22}Na lines.

1.2 New energy calibration with OSA 10

1.2.1 Temperature correction

The temperature and voltage dependence of the gains and offsets of the events rise time and pulse height was evaluated on ground and in flight [7]. In previous OSA versions, the temperature offset of each module with regard to the average was assumed to be constant, i.e., a stable thermal map. This assumption turned out to be wrong. A more accurate temperature correction has been introduced in OSA 10, in which the temperatures from the ISGRI thermal probes in each detector's module are used, instead of assuming a constant ΔT. The mean temperature of the ISGRI modules varies by $\sim$15–20°C, and the maximum temperature difference between the modules is about 3°C.

[1] ISDC Data Centre for Astrophysics, `http://www.isdc.unige.ch/`

[2] This energy is the mean obtained between the Kα_1 (59.3 keV) and Kα_2 (57.98 keV) lines [5]. Using the ratio I(α_2)/I(α_1)=0.57 from [6], the mean energy is 58.8297 keV.

[3] *INTEGRAL* Julian Date, IJD=MJD-51544.

1.2.2 Gain drift

In OSA 10, the gain drift is measured using the W and ^{22}Na background lines between revolutions 42 and 1106. To increase the statistics, particularly important in the ^{22}Na region, the background lines are measured in bins of 15 revolutions. The pulse height gain and offset are then described as a function of the pulse rise time and the time. Fig. 2 (left) shows the pulse height gain for different rise time intervals as a function of time. For energies below $\sim$50 keV, charge loss is negligible. We assume that the pulse height offset is constant and that the gain evolution does not depend on the rise time, and the gain is modeled with a linear function of time. For energies above $\sim$50 keV, the pulse height gain and offset are modeled both as a function of the rise time and time. After the correction, both background lines show a remarkably stable behavior, as shown in Fig. 1, with a relative energy variation below 1% around the nominal position (>6% in OSA 9). The FWHM of the W line increases by a factor 2 between revolutions 39 and 1142 (instead of 3 with OSA 9), indicating a better energy reconstruction.

2. Low threshold correction

The low threshold (LT) position is corrected with the new energy calibration (Fig. 2, right). The LT is stable in channel units. Since OSA 10, the LT shape follows the evolution of the spectral resolution, instead of being fixed at the W line resolution at the beginning of the mission as in previous OSA versions. Therefore, its resolution corresponds to the W line resolution, and also evolves with time. The accuracy achieved is around 1%. The jumps in Fig. 2 (right) correspond to different uploaded LT settings over the whole mission duration. After ten years in orbit, the lower threshold is still below 23 keV.

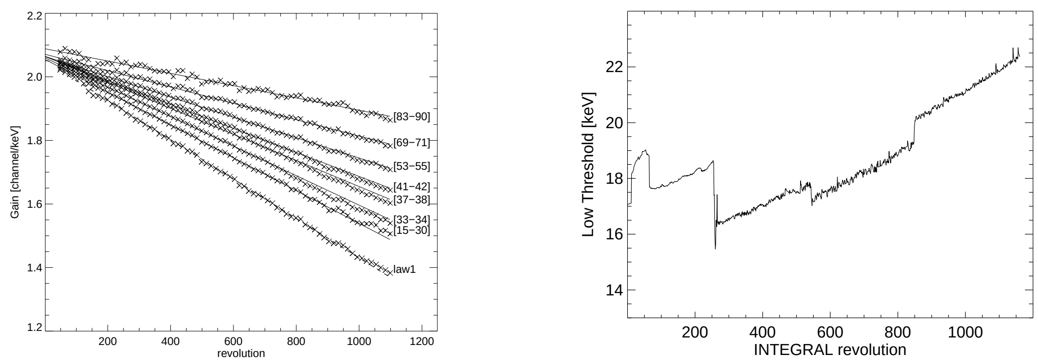

Figure 2: *Left:* Pulse height gain evolution for several rise time intervals (labeled in the figure) as a function of the revolution number. The linear fits used to describe the gain for the different rise time intervals are overplotted. The evolution of the gain for energies below $\sim$50 keV, for which a constant offset is assumed (see text), is also plotted, labeled as “law 1”. *Right:* Low threshold position with OSA 10.

3. Spectral analysis

Crab and background spectra extracted with OSA 9 and OSA 10 for a sample of revolutions are shown in Figs. 3 and 4. By comparing the left and right panels of Fig. 3, the OSA 10 correction

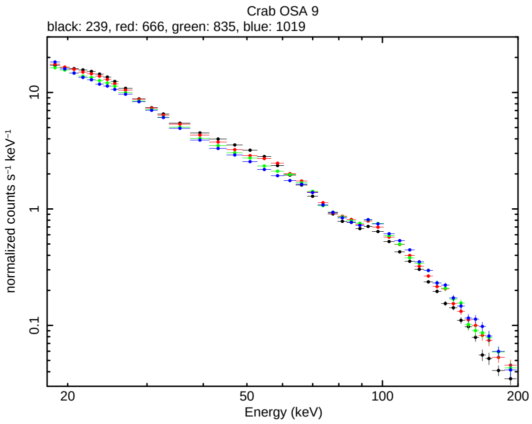

Figure 3: Crab spectra for a sample of revolutions (239, 666, 835, and 1019) extracted with OSA 9 (*left*) and OSA 10 (*right*).

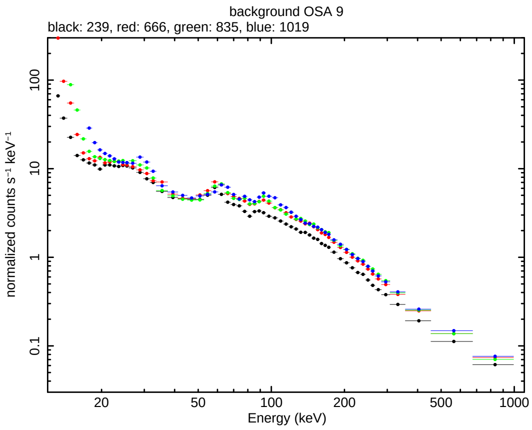

Figure 4: Background spectra for a sample of revolutions (239, 666, 835, and 1019) extracted with OSA 9 (*left*) and OSA 10 (*right*).

Table 1: Best fit parameters for the ISGRI Crab observation in revolution 839. 0.3% systematic errors are included. The quoted errors are at 90% confidence level.

Γ_1	Γ_2	$E_{\rm break}$ [keV]	norm [photons keV^{-1} cm^{-2} s^{-1} @ 1 keV]	$\chi^2_{\rm red}$/d.o.f.
2.070 ± 0.003	2.24 ± 0.03	94^{+6}_{-5}	8.6 ± 0.1	1.15/40

results in a more stable spectrum along the mission (especially at high energy) with respect to OSA 9.

A set of ancillary response files (ARFs) has been produced for different epochs using Crab observations. As an example, a fit of the Crab spectrum from revolution 839 extracted with OSA 10 is shown in Fig. 5. The parameters obtained from the spectral fit to a broken power law, reported in Table 1, are in good agreement with the expected values (see, e.g., [8]).

4. Cross-calibration

Using the results of the imaging extraction, we built Crab light curves in the three energy

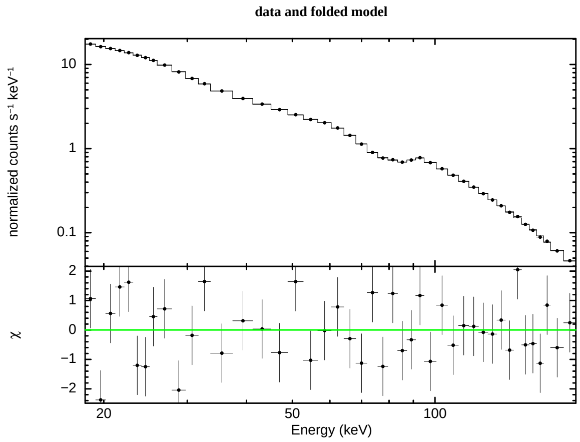

Figure 5: ISGRI Crab spectrum for revolution 839 (top) and residuals of best fit model (bottom) extracted with OSA 10.

bands 25–50, 50–100, and 100–200 keV. Figure 6 shows the comparison between the ISGRI count rate and that of other currently operational hard X-ray instruments, *Swift*/BAT [9] and *Fermi*/GBM [10]. For each instrument, the light curve has been renormalized to the average count rate measured during the period MJD=[54690, 54790], as in [11]. Note that the *Fermi*/GBM light curve in the highest energy band refers to the range 100–300 keV. The *Fermi*/GBM light curves are from the GBM Occultation Project[4]. For the *Swift*/BAT instrument, two different sets of light curves are reported, the 15–50 keV one being provided by the *Swift*/BAT Hard X-ray Transient Monitor pages[5], and the 25–50, 50–100, and 100–200 keV ones obtained from the Swift/BAT 58-months Hard X-ray survey[6]. In general, there is a very good agreement between the light curves measured with the different instruments. Small differences are observed in the 25-50 keV band for MJD<54000 between ISGRI and BAT, and at E>100keV at MJD>55600 between ISGRI and GBM.

5. Conclusions

A new energy correction has been implemented in OSA 10. The new calibration significantly improves the energy reconstruction. It includes a new description of the events gain and offset as a function of time and the events rise time, a more accurate temperature correction per ISGRI module, and a varying shape of the low threshold, corrected for the degradation of the spectral resolution. The background lines positions are remarkably stable. Very good agreement is obtained between the ISGRI long term Crab light curves and those obtained by other currently operational hard X-ray observatories, *Swift*/BAT and *Fermi*/GBM.

The limitations of the current energy calibration and known issues that the user should be aware of are kept up to date in the IBIS Analysis User Manual, in the section “Known Limitations”, available at the ISDC.

[4] `http://heastro.phys.lsu.edu/gbm/`

[5] `http://swift.gsfc.nasa.gov/docs/swift/results/transients/`

[6] `http://swift.gsfc.nasa.gov/docs/swift/results/bs58mon/index.php`

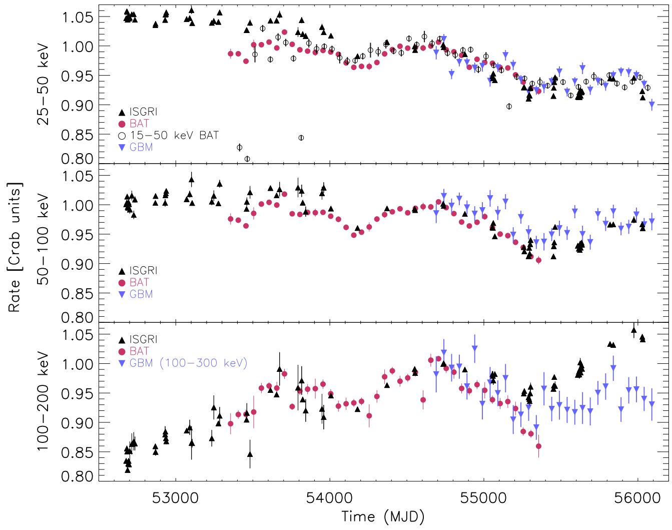

Figure 6: *INTEGRAL*/ISGRI, *Swift*/BAT, and *Fermi*/GBM Crab light curves over the period of the *INTEGRAL* observations. Each light curve has been renormalized to its average value measured during the period MJD=[54690, 54790].

Acknowledgments

The present work is partly based on observations with INTEGRAL, an ESA project with instruments and science data center (ISDC) funded by ESA members states (especially the PI countries: Denmark, France, Germany, Italy, Switzerland, Spain, Czech Republic and Poland, and with the participation of Russia and the USA). ISGRI has been realized by CEA-Saclay/DAPNIA with the support of the French Space Agency CNES. IC, JZH, and SS acknowledge financial support from CNES. FM acknowledges financial support from CNES and Pôle Emploi.

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