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Authors	SEGRETO, ALBERTO
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IBIS COMPTON MODE: ANALYSIS OF THE RANDOM COINCIDENCES

A. Segreto
IASF/CNR sezione di Palermo, Via Ugo La Malfa 156, 90136 Palermo, Italy

ABSTRACT

Data acquired in IBIS Compton mode are contaminated by 'fake Compton' events generated by random coincidences between ISGRI and PICsIT uncorrelated events.

In this paper we show how to compute the number of random coincidences, using two independent methods, and we present also a method for the subtraction of the random coincidences from the Compton data.

Key words: ISGRI; COMPTON; INTEGRAL.

1. INTRODUCTION

The IBIS instrument on board INTEGRAL satellite, is a coded aperture telescope, composed by two layers of pixellated and independent detectors: ISGRI (CdTe) and PICsIT (CsI). For a description of the instrument see Ubertini al. (2003).

When the time difference between an event detected by ISGRI and an event detected by PICsIT is within the onboard defined coincidence time window, the two events are associated and flagged as an IBIS Compton event (Forot al., 2004).

In addition to true coincidences, uncorrelated ISGRI and PICsIT events arriving within the coincidence window will be wrongly associated thus constituting 'fake Compton' events. These events contaminate the sky images, spectra, and pulse profiles extracted from Compton data, even after the usual background subtraction methods are applied.

In this work we derive formulas that allow us to compute the number of expected random coincidences with great accuracy and illustrate a method for the subtraction of the random coincidences from the Compton data.

2. EVALUATION OF THE RANDOM COINCIDENCE COUNT RATE

The time correlation between ISGRI and PICsIT events is tested by the IBIS on-board software. This process can be done only on-board since, in order to reduce the IBIS telemetry, the time resolution of the events transmitted to ground is degraded to 61 μsec from the original instrument time resolution which is

$$\delta T = 2^{-22}\ \mathrm{sec} \simeq 0.2384\ \mu\mathrm{sec} \qquad (1)$$

The Compton coincidence time window must be however wider than the time resolution of the instrument, to take into account that ISGRI events are generated with a jitter of the order of few μs with respect to the photon interaction times (Lebrun al., 2003).

The average electronic delay of ISGRI events with respect to correlated PICsIT events is compensated, by the on-board software, by adding an adjustable offset to the event arrival times. After this correction, a Compton scattered photon which interact in both detectors, generate an ISGRI event that can anticipate or follow the correspondent PICsIT event.

Denoting with T_{CdTe} and T_{CsI} the times associated to ISGRI and PICsIT events, they are considered correlated every time that

$$|T_{\mathrm{CdTe}} - T_{\mathrm{CsI}}| < \Delta T_{\mathrm{c}} \qquad (2)$$

where ΔT_{c} the Compton coincidence time window.

From this equation the rate of random coincidences can easily be obtained in the low count rate approximation and is given by

$$R = 2 \cdot \Delta T_{\mathrm{c}} \cdot R_{\mathrm{CdTe}} \cdot R_{\mathrm{CsI}} \qquad (3)$$

where R_{CdTe} and R_{CsI} are the ISGRI and PICsIT count rates.

In deriving Eq. 3 we have not considered, however, the effects of the finite time resolution of the instruments, that is, the fact that the time correlation process is not done by an electronic circuit, but by a

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software algorithm which can only handle the integer numbers obtained from the quantization of the event arrival times.

2.1. Effect of time quantization

Due to the finite time resolution of the instruments, the difference between the arrival times of any couple of ISGRI and PICsIT events cannot assume any value, but it is an integer multiple of the time resolution δT; it can then be expressed as

$$T_{\rm CdTe} - T_{\rm CsI} = \Delta n \cdot \delta T \tag{4}$$

where Δn is the difference between the time bin numbers associated to the events.

Of course, also the Compton coincidence time window can only be set to an integer multiple of the on-board time resolution, that is

$$\Delta T_{\rm c} = N_{\rm c} \cdot \delta T \tag{5}$$

where $N_{\rm c}$ is a parameter in the instrument configuration. In the IBIS nominal configuration $N_{\rm c} = 8$ so the coincidence time window is $\Delta T_{\rm c} = 8 \cdot 2^{-22} \simeq 1.9\ \mu$s.

In order to verify whether PICsIT and ISGRI events are correlated in time, the IBIS on-board software then tests the condition

$$|\Delta n| < N_{\rm c} \tag{6}$$

Neglecting the probability that more than two events can be detected within the coincidence time window $\Delta T_{\rm c}$, it can be easily demonstrated that the total rate of the random coincidences, obtained considering all the possible values that Δn can assume consistent with the condition in Eq. 6, is simply given by

$$R = (2N_{\rm c} - 1) \cdot r_0 \tag{7}$$

where r_0 is the rate at which ISGRI and PICsIT events are detected, by chance, within coincident time bins ($\Delta n = 0$).

Since $r_0 = \delta T \cdot R_{\rm CdTe} \cdot R_{\rm CsI}$, we obtain:

$$\begin{aligned} R &= (2N_{\rm C} - 1) \cdot \delta T \cdot R_{\rm CdTe} \cdot R_{\rm CsI} = \\ &= (2 \cdot \Delta T_{\rm c} - \delta T) \cdot R_{\rm CdTe} \cdot R_{\rm CsI} \end{aligned} \tag{8}$$

Note that the rate of random coincidences obtained from Eq. 8 is lower than the value predicted by Eq. 3 and that, as expected, the two values approaches if $\delta T \to 0$.

When the count rates are very high, and thus the probability that more than two events are detected within the same coincidence time window cannot be neglected, the formula for the computation of random coincidences becomes non-liner. A formula that reduces to Eq. 8 when the count rates are low, but that can be used also at higher count rates is

$$R = \frac{(2\Delta T_{\rm c} - \delta T) \cdot R_{\rm CdTe} \cdot R_{\rm CsI}}{1 + (2\Delta T_{\rm c} - \delta T)(R_{\rm CdTe} + R_{\rm CsI})} \tag{9}$$

Note that for every possible value of the parameters from this equation we always obtain $R < R_{\rm CdTe}$ and $R < R_{\rm CsI}$, which are conditions that must always be satisfied, even at very high count rates; in fact the rate of random coincidence can never be higher than the lowest of the rates of the two detectors.

In the computation of the random coincidences, it is also necessary to consider that Compton events are separated in 'Compton single'or 'Compton multiple' depending whether the PICsIT event is 'single' or 'multiple' (detected in one or more pixel).

The count rates of ISGRI events in coincidence with PICsIT 'single' and 'multiple' events respectively, can be obtained from Eq. 9 by simply replacing in its numerator the PICsIT total count rate ($R_{\rm CsI}$) with the count rate of PICsIT 'single' and 'multiple' events respectively.

3. DETERMINATION OF THE TRUE COMPTON COUNT RATE

Beside generating 'fake Compton' events which increase the Compton count rate, the random coincidences decrease the count rate of the ISGRI 'single' events by the same amount.

Denoting with $R_{\rm S1}$ the count rate of the ISGRI 'single' events, and with $R_{\rm S30}$ and $R_{\rm S31}$ the rates of 'Compton single' and 'Compton multiple' events, these rates are related by:

$$R_{\rm S1} = R_{\rm CdTe} - R_0 - R_1 \tag{10}$$

$$R_{\rm S30} = R_{\rm C0} + R_0 \tag{11}$$

$$R_{\rm S31} = R_{\rm C1} + R_1 \tag{12}$$

where $R_{\rm CdTe}$ is the true rate of the ISGRI 'single' events, $R_{\rm C0}$ and $R_{\rm C1}$ are the rates of the 'true Compton single' and 'true Compton multiple' events and R_0 and R_1 the rates of random coincidences for 'single' and 'multiple' events.

The count rates of the 'true Compton' events can then be obtained from

$$R_{\rm C0} = R_{\rm S30} - k_0 \cdot R_{\rm S1} \tag{13}$$

$$R_{\rm C1} = R_{\rm S31} - k_1 \cdot R_{\rm S1} \tag{14}$$

where the k_0 and k_1 are the fractions of random coincidences with respect to the ISGRI 'single' events, that is

$$k_0 = \frac{R_0}{R_{\rm S1}} = \frac{R_0}{R_{\rm CdTe} - R_0 - R_1} \tag{15}$$

$$k_1 = \frac{R_1}{R_{\rm S1}} = \frac{R_1}{R_{\rm CdTe} - R_0 - R_1} \tag{16}$$

Simple approximate formulas to compute these coefficients can be obtained assuming that R_0 and R_1 are negligible with respect to $R_{\rm CdTe}$; using Eq. 3 for the computation of the rate of random coincidences we get (with limited accuracy)

$$\begin{aligned} k_0 &\simeq 2 \cdot \Delta T_{\rm c} \cdot (R_{\rm CsI})_{\rm single} & (17) \\ k_1 &\simeq 2 \cdot \Delta T_{\rm c} \cdot (R_{\rm CsI})_{\rm multiple} & (18) \end{aligned}$$

To give a numerical example, that shows the level of approximation that can be obtained using these equations, we consider the Crab observation in rev. 39. The count rates during this observation were:

$$\begin{aligned} (R_{\rm CsI})_{\rm single} &= 2916 \text{ cts/sec} \\ (R_{\rm CsI})_{\rm multiple} &= 632.5 \text{ cts/sec} \\ R_{\rm S1} &= 878 \text{ cts/sec} \\ R_{\rm S30} &= 101.7 \text{ cts/sec} \\ R_{\rm S31} &= 32.4 \text{ cts/sec} \end{aligned}$$

Considering that during this observation the Compton coincidence window was $\Delta T_{\rm c} = 5$ μsec, from Eq. 17 we get the approximate value $k_0 = 2.92\%$, while using Eq. 15 and Eq. 9 the value obtained is $k_0 = 2.83\%$.

As evident, the approximation is quite good, however, the small difference between the two values can be significant when a perfect subtraction of random coincidences is required.

3.1. Measurement of the random coincidences with the ISGRI noisy pixels

In the previous section we have shown how to evaluate, theoretically, the number of random coincidences. Another method that allow us to measure, directly from the data, the fraction of random coincidences, is the analysis of the events generated by the ISGRI noisy pixels.

The ISGRI noisy pixels are pixels that due to electronic noise generate an high number of false events; these events are mostly concentrated in the lowest channels of the ISGRI energy spectra, below the detection threshold of true energy deposits ($\sim$ 15 keV).

Events generated by electronic noise, of course, do not have any temporal correlation with the PICsIT events; however, a fraction due to the random coincidences will be flagged as Compton. If we then select in the Compton data the events in the lowest energy channels of a set of ISGRI noisy pixels, all the selected events have been surely generated by random coincidences.

If we denote with $R_{\rm S1n}$ the count rate in the lowest energy channels in the ISGRI 'single' event dataset and with $R_{\rm S30n}$, $R_{\rm S31n}$ the count rate associated to the same set of pixels and in the same energy channels, but in the 'Compton single' and 'Compton multiple' dataset, we can directly obtain the fraction of random coincidences:

$$\begin{aligned} k_0 &= R_{\rm S30n}/R_{\rm S1n} & (19) \\ k_1 &= R_{\rm S31n}/R_{\rm S1n} & (20) \end{aligned}$$

As example, for the Crab observation in rev. 39 previously considered we have measured in the low energy channels of a selected set of noisy pixels, the following count rates:

$$\begin{aligned} R_{\rm S1n} &= 27.9 \text{ cts/sec} \\ R_{\rm S30n} &= 0.79 \text{ cts/sec} \end{aligned}$$

From their ratio we get $k_0 = 2.83\%$ which is fully consistent with the value theoretically expected. This confirms the correctness of the analysis of the random coincidences done in the previous section.

4. CLEANING OF THE COMPTON DATA

The 'fake Compton' events have the same spatial distribution of the ISGRI 'single' events so they produce in the Compton sky images obtained by deconvolution of ISGRI shadowgram, a scaled replica of the skymap of the ISGRI 'single' events. The contribution of the random coincidences must then be accurately subtracted to avoid fake source detections in the Compton data.

We have shown in the previous section how to evaluate with high accuracy the total number of random coincidences. However, if we apply any kind of filtering to the Compton data (e.g. selection on the reconstructed Compton Energy or Compton scattering angle) the number of 'fake' events accepted after the selection, become an unknown quantity.

The only way to keep track of the number of 'fake events' after every possible event selection is to generate a file containing only 'fake events' on which exactly the same event selection can be applied as to the Compton data.

This file can be generated by associating a randomly chosen PICsIT 'single' or 'multiple' event to each ISGRI 'single' event. It is evident that the file generated in this way is statistically representative, a part from a scaling factor, for the 'fake' events in the unfiltered Compton data; the scaling factor is the same coefficient (k_0 or k_1) that can be determined as shown in the previous section.

If we then process the file of 'fake Compton' events in exactly the same way as we process the Compton data, the events in the file will remain representative with the same original scaling factor fro the 'fake' events in the filtered Compton data.

The procedure for the subtraction of the random coincidences is then the following:

- generate a file of 'fake Compton' events ('single' or 'multiple') by the random association of the ISGRI 'single' events with the PICsIT 'single' or 'multiple' events
- filter and process in exactly the same way the Compton data and the 'fake Compton' file
- compute the scaling factors for the considered acquisition (k_0 for 'single' or k_1 for 'multiple' events) using the analytical method or measuring it from the ISGRI noisy pixels spectra
- subtract from the products generated from Compton data (skymaps, spectra, pulse profiles) the same product obtained from the 'fake Compton' file, scaled by k_0 and for 'single' or by k_1 for 'multiple' events.

Of course, if during the observation PICsIT is in histogram mode (which is the nominal configuration), the list of its events is not available on ground, so to generate the file of 'fake events' it is necessary to use PICsIT data taken from another acquisition with the instrument in 'photon by photon' mode. This introduces in most cases a negligible approximation since the PICsIT total background count rate is in any case much higher than any additional source count rate.

Particular attention in the subtraction of random coincidences must be paid to the event selections which are applied directly on-board in order to reduce the amount of IBIS telemetry.

As an example, since an on-board Rise Time selection is applied to the ISGRI 'single' events but not to the Compton data, for the correct application of the method the same selection must be applied on-ground to the Compton data otherwise the file of 'fake events' will not be perfectly representative of the contamination in the Compton data.

Examples of subtraction of random coincidences on calibration data and on the Crab observations, are given in Segreto (2004).

5. CONCLUSION

Due to random coincidences the IBIS Compton data are contaminated by 'fake' events generated by the random coincidences between uncorrelated ISGRI and PICsIT events.

Since 'fake Compton' events can generate false source detections in the Compton data, it is very important to quantify their number with an high precision.

We have analyzed in detail the way the on-board software performs the time correlation of the events, deriving formula that allow us to compute the number of random coincidences by taking also into account small effects that are introduced by the finite time resolution of the instruments and by their quite high count rates.

The result of this analysis has been fully confirmed by measuring the amount of random coincidences in the ISGRI noisy pixels spectra. With both methods we have obtained identical results.

We have subsequently illustrated a method for the subtraction of the random coincidences from any kind of product that can obtained from the Compton data (e.g. skymaps, spectra, pulse profiles).

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