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# A new determination of the *INTEGRAL*/IBIS point source location accuracy

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## ABSTRACT

**Aims.** To determine the Point Source Location Accuracy (PSLA) for the *INTEGRAL*/IBIS telescope based on analysis of archival in-flight data.

**Methods.** Over 40000 individual pointings (science windows) of *INTEGRAL*/IBIS data were analysed using the latest Off-line Science Analysis software, version 7.0. Reconstructed source positions were then compared against the most accurate positions available, determined from focusing X-ray telescopes. Since the PSLA is a strong function of source detection significance, the offsets from true position were histogrammed against significance, so that the 90% confidence limits could be determined. This has been done for both sources in the fully coded field of view (FCFOV) and partially coded field of view (PCFOV).

**Results.** The PSLA is found to have improved significantly since values derived from early mission data and software for both FCFOV and PCFOV.

**Conclusions.** This result has implications for observers executing follow-up programs on IBIS sources since the sky area to be searched is reduced by >50% in some cases.

**Key words.** Instrumentation: detectors, Methods: data analysis

## 1. Introduction

The *INTEGRAL* satellite (Winkler et al. 2003), launched in October 2002, is an ESA space mission specifically designed to study the gamma-ray sky. In particular the IBIS (Imager on Board of the *INTEGRAL* Satellite) telescope (Ubertini et al. 2003) is the main hard X-ray/soft gamma-ray coded aperture imaging instrument (Goldwurm et al. 2003), and is responsible for surveying and cataloguing the sky above 17 keV. Here we discuss the point source location accuracy (PSLA) of the ISGRI low energy detector (15-1000 keV) of IBIS (Lebrun et al. 2003).

Due to the continuing necessity to follow-up the growing unidentified *INTEGRAL* source population in other wavebands (particularly optical and infrared), it is of great interest to assure the correctness of the IBIS/ISGRI PSLA. In particular, it is hoped that with the release of new and updated Off-line Science Analysis (OSA 7.0) software the PSLA could have improved substantially compared to the already published estimates based on early mission data and software releases (Gros et al. 2003, constructed the PSLA based upon OSA 3.0). Any improvement in the PSLA is important in reducing the chance of random or multiple source associations in other wavebands.

## 2. Refining the PSLA error radius

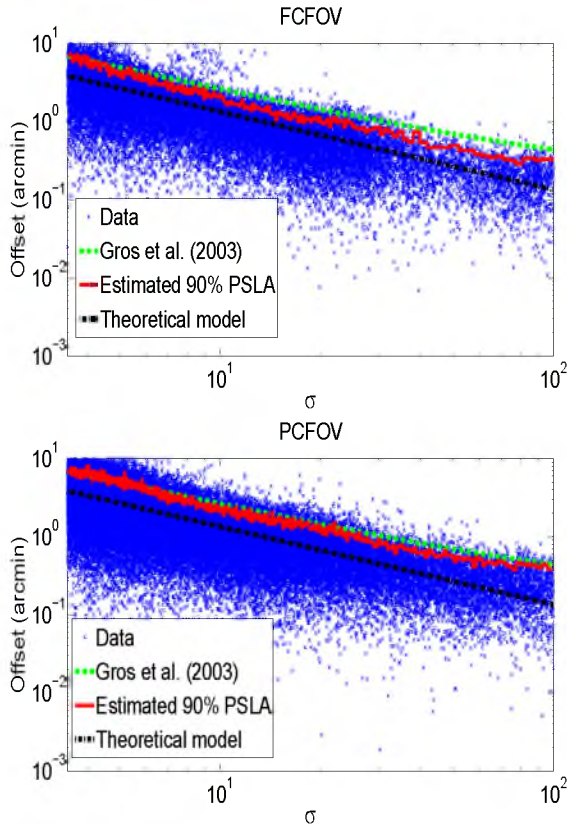
In order to empirically determine the PSLA of the IBIS/ISGRI telescope, we can extract the positions of objects from the IBIS/ISGRI Science Windows<sup>1</sup> (ScWs) and compare these with their best known positions. This can then be used to estimate the 90% error offset as a function of detected significance, allowing us to define the 90% PSLA. In particular, the IBIS/ISGRI telescope (and coded mask telescopes in general) PSLA depends strongly on detection significance, but also on the position of the source within the field of view. We therefore require for our analysis a set of sources spanning a wide range of significances and off-axis positions in order to allow our analysis to be useful for all detected IBIS/ISGRI sources.

We begin by compiling a list of sources with good positions. It is best at this stage to be conservative and only select sources where accurate nominal positions are known rather than to bias our sample by also including sources with large nominal error radii, like many newly discovered *INTEGRAL* sources. To do this we take the latest *INTEGRAL* General Reference Catalog (Version 30, Ebisawa et al. 2003, <http://isdc.unige.ch/Data/cat/latest/>) and make a

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<sup>1</sup> An IBIS/ISGRI Science Window refers to one single *INTEGRAL* pointing of about 2000 seconds

selection on the error radius, selecting those sources with an error less than  $30''$ ; at this level, the error on the true position should give a negligible contribution to the measured offsets to the IBIS position. Thus the total number of objects used in our sample is 332, spanning a wide range of detection significances and off-axis angles. This number might seem small when compared to the 721 sources detected in Bird et al. (2010), however we note that many objects in that catalog are newly discovered *INTEGRAL* sources for which X-ray follow-up is not yet available, and that therefore have relatively large nominal error radii.



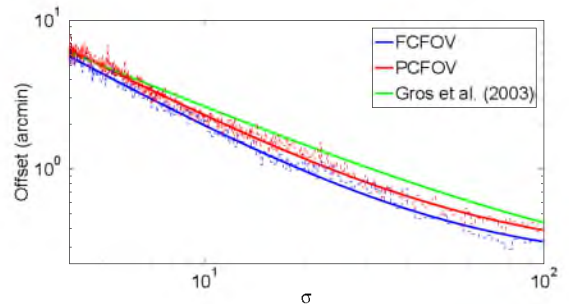
**Fig. 1.** Measured offset from true position (datapoints) as a function of detection significance for IBIS/ISGRI detected sources in the (upper) fully coded field of view and (lower) partially coded field of view. Also plotted is the estimated 90% PSLA from Gros et al. (2003) (dashed line), our estimated 90% PSLA (solid line) and the telescope theoretical PSLA from Goldwurm et al. (2001) (dashed-dotted line).

After performing an imaging analysis with the OSA 7.0 pipeline, we inspected all available ScW images and extracted the fitted positions which resulted from the image deconvolution; these are the columns RA\_FIN and DEC\_FIN from the `isgri_sky_res` file for all pointings where any of the 332 objects was present. The dataset was divided into fully coded field of view (FCFOV) and partially coded field of view (PCFOV). The IBIS coded aperture mask has a field of view of  $30^\circ$ , the FCFOV is the central  $9^\circ \times 9^\circ$  region; everything outside of this region constitutes the PCFOV. We then determine the offset as a function of detection significance in both FCFOV and PCFOV, for all objects in question, allowing us to estimate the 90% PSL confidence by adaptively binning the measured offsets in significance in order to have the same statistics for all bins (100 measurements per bin). Around 25000 and 75000 individ-

**Table 1.** Estimated PS LA fit parameters for the FCFOV and the PCFOV.

	FCFOV	PCFOV
65%	$a = 17.65$ $b = 0.14$ $c = -1.19$	$a = 18.78$ $b = 0.17$ $c = -1.16$
90%	$a = 31.1$ $b = 0.23$ $c = -1.25$	$a = 31.1$ $b = 0.25$ $c = -1.18$
95%	$a = 36.7$ $b = 0.25$ $c = -1.24$	$a = 34.8$ $b = 0.26$ $c = -1.14$
99%	$a = 36.4$ $b = 0.14$ $c = -1.04$	$a = 34.6$ $b = 0.19$ $c = -0.97$

ual offset measurements are used in the FCFOV and PCFOV analyses respectively. The results are shown in Figure 1 with the solid line representing the 90% confidence limit, whilst the dashed line shows the result from Gros et al. (2003) and the dashed-dotted line shows the theoretical PS LA as defined by Goldwurm et al. (2001). Note that the theoretical PS LA of Goldwurm et al. (2001) applies only for on-axis sources, whilst the estimated 90% PS LA from Gros et al. (2003) is derived for sources within 14 degrees of the telescope axis.



**Fig. 2.** Fits to the OSA 7.0 90% PS LA in FCFOV and PCFOV. In each case, the solid line represents the best fit. Also plotted is the 90% PS LA estimate of Gros et al. (2003).

In order to fit the estimated 90% PS LA we have used the form  $y = ax^c + b$  (the same as used by Gros et al. 2003), and applied the same weights for all bins as they contain the same number of observations. Similarly for completeness we also estimated the 65%, 95% and 99% PS LA. The fit parameters for all estimated PS LA are shown in Table 1, whilst we display only the 90% PS LA in Figure 2.

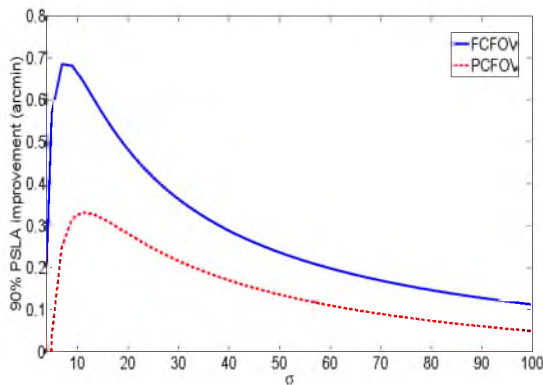
### 3. Comparison to previous results

These empirical fits can now be used in order to estimate the improvement in radius and area between the previously published fit of Gros et al. (2003) and our own estimates. To this end, Figure 2 shows once again our fits for the 90% PS LA for the FCFOV and PCFOV and the Gros et al. (2003) result. To demonstrate the decrease in error radius between the Gros et al. (2003) result and our new updated PS LA we simply subtract the two fits in order to display the error radius improvement. This is shown in Figure 3, where it can be seen that the biggest reduction in radius occurs at approximately  $10\sigma - 15\sigma$ . The potential

for reducing false matches when performing follow-up observations of such objects in other wavebands is however best shown in Figure 4, where the percentage area improvement of the 90% error circle is shown. This is defined to be the area subtended by our 90% PSLA as a function of significance divided by the area subtended by the 90% PSLA estimate of Gros et al. (2003). Here the biggest reduction occurs in the range  $20\sigma - 25\sigma$ , where the area to inspect reduces by  $\approx 50\%$  from the previous Gros et al. (2003) result. This would be a typical significance for a transient detection in a single ScW of a source of  $\sim 250\text{mCrab}$ . We therefore predict that these transient detections will benefit the most from this improved 90% PSLA, where the probability of false matches for follow-up observations will be drastically reduced.

*INTEGRAL*/IBIS has also detected and classified a large number of persistent sources such as AGN, which obtain their peak significance after mosaicking many individual ScWs. In this case it is not always easy to establish how many pointings were used where the source candidate was in the FCFOV or the PCFOV, and so it is not trivial to establish which 90% PSLA to use. In these cases we suggest a conservative approach and use the PCFOV PSLA estimate.

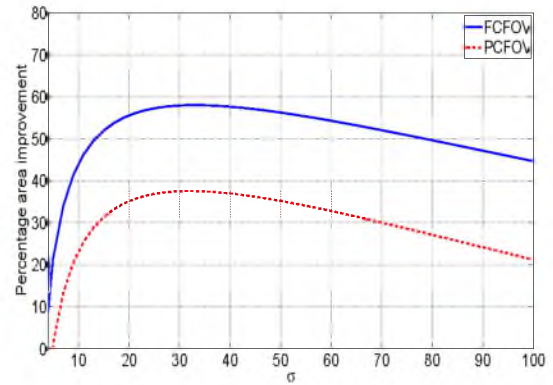
We have also carried out the same analysis for data reduced with an older version of the analysis software, OSA 5.0, and find after fitting the 90% PSLA, that an improvement on the estimated error circle size had already been achieved with OSA 5.0 compared to the Gros et al. (2003) result based on OSA 3.0; however with the latest version of the software release, OSA 7.0, the improvement is even more evident. This result also indicates that a re-analysis of archival data with the latest software will often yield far better source positions, and may allow observers to distinguish between multiple candidate counterparts far better than previously.



**Fig. 3.** 90% PSL error radius improvement between the old Gros et al. (2003) and the new (this work) estimates in arcminutes.

#### 4. Conclusions

This work has shown that the IBIS/ISGRI PSLA (ie the size of the 90% error circle) has dramatically improved since the last study of Gros et al. (2003) and this can be attributed to improvements in the *OSA* software. The main implications of this result will be for follow-up observations, particularly in the optical and infrared wavebands, of the *INTEGRAL* unidentified source population ( $\approx 30\%$  of objects present in the latest IBIS/ISGRI catalogue release by Bird et al. 2010). This improved error radius



**Fig. 4.** Percentage sky search area improvement between the old Gros et al. (2003) and the new (this work) 90% error radii.

will greatly enhance the identification of *INTEGRAL* counterparts.

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