INTEGRAL/IBIS 7-year All-Sky Hard X-ray Survey

I. Image reconstruction

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ABSTRACT

This paper is the first in a series devoted to the hard X-ray whole sky survey performed by the INTEGRAL observatory over seven years. Here we present an improved method for image reconstruction with the IBIS coded mask telescope. The main improvements are related to the suppression of systematic effects that strongly limit sensitivity in the region of the Galactic plane (GP), especially in the crowded field of the Galactic center (GC). We extended the IBIS/ISGRI background model to take into account the Galactic ridge X-ray emission (GRXE). To suppress residual systematic artifacts on a reconstructed sky image, we applied nonparametric sky image filtering based on wavelet decomposition. The implemented modifications of the sky reconstruction method decrease the systematic noise in the ~20 Ms deep field of GC by ~44%, and practically remove it from the high-latitude sky images. New observational data sets, along with an improved reconstruction algorithm, allow us to conduct the hard X-ray survey with the best currently available minimal sensitivity 3.7 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} \sim 0.26 \text{ mCrab} in the 17–60 keV band at a 5σ detection level. The survey covers 90% of the sky down to the flux limit of 6.2 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2} (\sim 4.32 \text{ mCrab}) and 10% of the sky area down to the flux limit of 8.6 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} (\sim 0.60 \text{ mCrab}).

Key words. methods: data analysis – methods: observational – techniques: image processing – surveys – X-rays: general – Galaxy: general

1. Introduction

Since its launch in October 2002, the INTEGRAL observatory (Winkler et al. 2003) has gathered a huge observational data set that allows us to perform the most sensitive hard X-ray survey to date. The main scientific results and source catalogs have been reported in many relevant papers concerning partial sky coverage (e.g. Revnivtsev et al. 2003; Molkov et al. 2004; Krivonos et al. 2005; Revnivtsev et al. 2006a; Bird et al. 2004, 2006, 2007; Bassani et al. 2006; Bazzano et al. 2006) and full sky studies (Krivonos et al. 2007b; Sazonov et al. 2007; Beckmann et al. 2009; Bird et al. 2010).

Recently, great progress in surveying the hard X-ray sky was achieved with the Burst Alert Telescope (BAT; Barthelmy et al. 2005) at the Swift observatory (Gehrels et al. 2004). The Swift/BAT survey provides very homogeneous sky coverage in the 15–195 keV energy band with a current maximum sensitivity of 2.2 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}. The distribution of survey sensitivity peaks in the extragalactic sky. The survey results and source catalogs have been reported in papers by Tueller et al. (2010) and Cusumano et al. (2010). As seen from the large sample of detected active galactic nuclei (AGNs), the results of the Swift/BAT survey are very valuable for extragalactic studies. However, due to the relatively poor angular resolution of the instrument, its imaging capabilities in the regions of Galactic plane (GP) and especially the Galactic center (GC) are limited. On the other hand, the sky coverage by the Swift/BAT survey is nearly uniform, therefore only a small fraction of its total operational time was devoted to observations of the Galaxy.

In contrast to Swift, the INTEGRAL observatory provides an all-sky survey with exposure more concentrated in the GP, having a typical limiting flux of less than 1.43 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2} (1 \text{ mCrab}) in the working energy range 17–60 keV. With an angular resolution almost twice as good for Swift/BAT, one can effectively disentangle sources in such crowded regions as the GC. This makes the Swift/BAT and INTEGRAL surveys complementary.

INTEGRAL has already accumulated a lot of exposure time in the direction of the GP with a maximum of ~20 Ms of nominal time in the direction of the GC. However, the growing exposure time devoted to the GP and GC is not reflected by a corresponding increase in survey sensitivity. Observations in these regions are strongly affected by the systematics related to the crowded field of the GC and strong Galactic X-ray background radiation.

In this work we address the question of improving the sensitivity of the ongoing INTEGRAL hard X-ray survey. In Sect. 2 we discuss several aspects of the sky reconstruction method of the IBIS coded-mask telescope (Ubertini et al. 2003). In Sect. 3 we implement Galactic background corrections to the sky.
reconstruction method. Section 4 introduces a modified sky reconstruction method with sky image filtering procedure based on à trous wavelet decomposition. The properties of the resulting all-sky survey are presented in Sect. 5.

Throughout the article the exposure will be expressed taking instrumental dead time into account, i.e. showing the effective exposure time, rather than the total exposure.

2. General sky reconstruction method

IBIS is a coded aperture imaging telescope. The sky is projected onto the detector plane through the transparent and opaque elements of the mask mounted above the detector plane. Generally, the sky reconstruction is based on the deconvolution of the detector image with a known mask pattern. We (EC) developed IBIS/ISGRI sky reconstruction method and have partially described it in our previous publications (Revnivtsev et al. 2004; Krivonos et al. 2005, 2007a,b). The basic idea we used is presented in Fenimore & Cannon (1981) and Skinner et al. (1987). For the standard IBIS/ISGRI analysis we refer the reader to the paper by Goldwurm et al. (2003). Here we outline only those steps that are essential for this study.

2.1. IBIS telescope coding aperture

The quality of the reconstructed sky image directly depends on our understanding of the coding procedure. For example, the mask’s supporting structure can significantly reduce the number of low-energy photons passed though the open mask elements. Other assembly elements like screws, plates, and glue strips attaching the IBIS mask to the supporting structure also block the incoming photons, modifying the shadow cast by a point source on the detector.

In our package we implemented the best known configuration of all the known elements of the telescope, which contribute to the shadowgram. We could not find the exact size of the assembly screws that attach the mask, plates and glue strips. The approximate parameters of these elements were found by comparing real and model detector shadowgrams illuminated by a strong source at different azimuthal angles.

2.2. Detector exposure

In general the detector image, produced when observing $M$ point sources with an underlying flat sky background, can be represented by the superposition of shadow patterns of sources (“pixel illumination fraction”, PIF) and the detector background map $B$:

$$ D = \sum_{i=0}^{M} f_i PIF_i + k_B B, $$

where $f_i$ is the source flux, $B = B_{\text{CXB}} + B_{\text{det}}$ represents a detector background map, containing photon counts from cosmic X-ray background (CXB), and detector instrumental noise. We assume that the detector illumination by CXB and intrinsic ISGRI background have a similar pattern, and can be merged into the background map $B$. The last is estimated by an accumulation detector image over a large number of observations without strong sources in the field of view. Obviously, background map $B$ should contain the current detector background pattern due to the long-term variation in background environment related to the Sun and cosmic rays (Lebrun 2005). For a given observation, we use a background map accumulated during the nearest set of extragalactic observations. Typically, we construct a new background map for every ~50–70 spacecraft orbits (150–200 days).

When two sources are located close to each other (at separation comparable with IBIS/ISGRI angular resolution), the direct solution of Eq. (1) for flux $f_i$ can be unstable giving results with infinite errors. In other words, the detector count rate in a given sky direction can be explained by two (or more) sources having any absolute flux.

2.3. Replicated mask pattern

IBIS mask has replicated patterns (see Reglero et al. 2001; Ubertini et al. 2003; Goldwurm et al. 2003). This pattern of the mask has an advantage because, ideally, it has a much narrower point spread function and flat side lobes in the central part of the reconstructed image (Fenimore & Cannon 1978). But at the same time it causes serious complications because of the very significant side peaks of the point spread function. This means that a simple deconvolution algorithm sees “ghost” sources at certain sky positions (see Figs. 1 and 2), related to the position of the real source and the size of the replicated mask pattern.

The sources in a variety of sky positions within a field of view create shadows with similar patterns, which causes uncertainty in the source flux determination (the direct solution of Eq. (1) is impossible). Unfortunately, this situation is not rare in the crowded field of the GC, as shown in Fig. 3. Due to observational constraints, IBIS FOV was mainly co-aligned...
with axes of the equatorial coordinate system (“N-E” notation). As a result, there are a number of bright sources which permanently appeared in mutual “ghost” positions. This leads to an additional uncertainty of the source flux determination. The following source pairs can be affected by mutual flux interplay: GX 340+0 and XTE J1743-363, XTE J1701-462 and GX 349+2, GX 9+9 and GX 13+1, and the triplet GX 1+4, XTE J1818-245 and GX 17+2.

2.4. Iterative removal of cataloged sources

For a good quality all-sky map, suitable for searching for new weak sources, the ghosts of known bright sources have to be removed. This is done during the reconstruction of images of individual observations (ScWs) with an effective exposure of 1–3 ks. Instead of a blind search for bright sources in each individual observation we use a catalog of known sources to control the removal of ghosts. Indeed, for many regions of the sky, the final map is the result of stacking hundreds and thousands of individual observations. Therefore, a relatively weak object, far too faint to be detected in an individual observation, may appear as a very significant source in the final map. Since the amplitude of the ghosts scales with the intensity of the true source, it is clear that ghost removal should be applied even to objects that are too faint to be detected in individual science windows. For crowded fields (like the GC region), this implies that ghosts of some 100 sources should be removed in individual observations.

The whole procedure requires not only the list of sources to be removed from the detector image, but also a sequence of Iterative Removal Of Sources (IROS, see Goldwurm et al. 2003; Krivonos et al. 2005). It is expected (and confirmed by direct tests) that the brightest (most significant) objects have to be removed first, since the source flux \( f \) is evaluated by assuming that there is only one source in the field of view. The significance of the source detection is evaluated by reconstructing an image prior to iterative source removal and checking the fluxes at the positions of cataloged sources. The list of objects ranked according to their significance is then used as input for iterative source removal procedure. This poses the problem of ranking weak sources, since their flux (and ranking) is determined with a large uncertainty in the individual science window (e.g. the flux from the source can be negative). We made several tests with various ranking schemes for weak (less than 3\( \sigma \) detection) sources, checking the rms of the final maps and fluxes of cataloged sources. The final scheme implemented in our analysis uses the absolute value of the source detection significance to rank the order of source removal.

2.5. ISGRI pixel filtering

As described in Krivonos et al. (2007b) the hot and dead ISGRI detector pixels were screened from the analysis. This was done using quite crude filtering criteria and some noisy pixels may still be present on the detector shadowgram. They may not be visible on an individual detector image, but can be revealed by those accumulated over several observations.

To estimate the effect induced by “noisy” pixels, we simulated a detector image for a typical ScW exposure of 2 ks, and inserted one pixel in an arbitrary position exceeding the mean detector count rate (40 cnts/pix/ScW) by a factor of ~2.5 (~9.5 standard deviations). For a typical ScW such a weak peculiar pixel introduced negligible systematic noise and the reconstructed sky was dominated by Poisson statistics. However, with increasing exposure, the effect became more significant. We accumulated the mosaic image of a 280 ks staring observation of NGC 4151 with a simulated detector and one hot pixel. When the position of a noisy pixel was randomly distributed on a detector in every observation, the total mosaic did not contain any significant systematic residuals. When a noisy pixel was fixed on the detector, the standard deviation of reconstructed sky was ~20% higher, than without a hot pixel on the detector.

To perform additional ISGRI pixel cleaning, we followed the general approach also employed by Eckert et al. (2008). We stacked detector images obtained during the spacecraft orbit after removing flux from known X-ray sources (Sect. 2.4), detector background map \( B \) (Sect. 2.2), and Galactic X-ray background (Sect. 3). The distribution of pixels on a stacked detector image was described well by Gaussian with zero mean. Thus we expected that 99.7% of the pixels have a value in the range \([-3\sigma, +3\sigma]\). The ISGRI detector contains 128 \( \times \) 128 pixels, which gives us ~50 of them with an expected value greater than 3\( \sigma \). However, we typically detected 200–300 deviations from zero to over 3\( \sigma \). We removed these pixels from further analysis. Filtering done in this way reduces the detector area by ~2%, and has a minor effect on flux from serendipitous, faint sources.

3. Galactic background

During observations of the GC region, the IBIS field of view contains many discrete sources (Fig. 4). But in contrast to high galactic latitude observations, the underlying sky background is not flat. From early X-ray observations we know that the Galaxy reveals itself as a strong diffuse emitter (e.g. Worrall et al. 1982). The morphology of the Galactic X-ray background at energies above 20 keV is now relatively well known. As shown in recent RXTE and INTEGRAL investigations (Revnivtsev et al. 2006b; Krivonos et al. 2007a), the X-ray background is traced by the near-infrared brightness of the Galaxy (blue contours in Fig. 4). We refer to the Galactic X-ray background later as “Ridge” emission or GRXE (Galactic ridge X-ray emission).

The measured 17–60 keV GRXE intensity per IBIS FOV reaches 200 mCrab in the region of the Galactic bulge. Such strong emission will not appear on a deconvolved IBIS/ISGRI

\footnote{All observations performed in “staring” mode have fixed orientation and the roll angle of the telescope.}
Fig. 3. INTEGRAL/IBIS hard X-ray (17–60 keV) map of the sky region around the GC. The green squares demonstrate the relative sky positions of false side peaks (“ghosts”, see Fig. 1) of selected bright sources.

Fig. 4. Two relative alignments of the GP in the IBIS FOV, left centered and the right shifted along the galactic latitude. The blue contours are isophotes of the 4.9 \( \mu \text{m} \) surface brightness of the Galaxy (COBE/DIRBE) revealing the bulge/disk structure of the inner Galaxy. The NIR brightness of the galaxy traces the hard X-ray ridge emission. The small and large rounded squares on each plot demonstrate the full and partial coded areas, respectively. The points show sky positions of the hard X-ray sources detected on the 20 Ms time-averaged map (Figs. 11 and 3). A signal-to-noise ratio of the sources is shown by black (5–10), blue (10–30), and red (>30). The difference in detector illumination by the Ridge is shown in Fig. 5.
some curvature. In contrast, detector variations have a significant gradient when the GP intersects FOV several degrees away from its center (position “B”). That configuration strongly warps the detector image, which will obviously affect the source flux estimates and, consequently, the accuracy of the source shadowgrams removal.

The impact of this Ridge emission in the IBIS FOV to the reconstructed sky image is significant. The comprehensive demonstration of this effect directly on the GC data is not possible due to more serious related to the very complicated detector exposure to many bright sources. That is why, in order to show the Ridge contribution in the reconstructed sky, we used the relatively simple and clean 280 ks observation of NGC 4151 for reference (Fig. 8, left). The artificial detector Ridge component with actual normalization measured in the GC (position “B”) was added to the detector image of every spacecraft observation. Since we used staring observations, this operation was equivalent to placing Ridge on the sky 7” away from the NGC 4151. The quality of the final mosaic (Fig. 6, left) was very poor and the signal-to-noise ratio (hereafter $S/N$) distribution of pixels had strong non-Gaussian wings (Fig. 6). The standard deviation of image was 1.7, in contrast to 1.3 of the referenced sky. Thus, we can conclude that the Ridge emission can introduce significant systematic noise to the reconstructed sky. However the degree of image worsening depends on the exposure and pattern of the observations.

We next consider the typical IBIS/ISGRI observation of the GC region (position “A”), as the most representative observation containing many bright sources and strong Ridge emission in the FOV. The detector image is shown in the left frame of Fig. 7. For comparison we show on the right the detector image containing only one bright source in FOV. The observations were separated by a 10-h time interval when the background count rate had not changed significantly, i.e., the background map for both images is the same. In the right image the background and source counts are clearly distinguished. This leads to straightforward application of the standard coded mask reconstruction algorithm (Sect. 2). The left image contains many overlapping shadowgrams of bright sources. The assumed background model is not accurate and the general method is confused.

The catalog of predefined source positions in the GC provides about a hundred objects in the FOV. Among them, 6–8 bright sources are usually detected with $S/N > 5$ in the typical ∼2.5 ks observation. By summing up all PIFs of these sources, one can show that practically all detector pixels are illuminated by at least one source, which is seen in the left image of Fig. 7. This means that any measurements of source fluxes in the GC will be affected by the correlations of source shadowgrams, especially for those having replicated patterns due to the periodic mask elements. Furthermore, there are no source-free pixels to estimate the background count rate. Flux measurement, based on the balance matrix (Krivonos et al. 2005; Goldwurm et al. 2003) is inaccurate, because the background map for a given source is strongly affected by other sources. The general reconstruction algorithm works “as is”, trying to estimate the fluxes of the brightest source and leaving many systematic artifacts on the detector and consequently, on the resulting sky image.

The situation is further complicated by the fact that practically all ISGRI pixels are illuminated at the same time by the Ridge emission (see Fig. 5). This leads to a high correlation between shadowgrams of a manifold of sources and the Ridge.

Summing up all mentioned effects, we conclude, that Eq. (1) based on simple background map $B$ is unsuitable for Galactic observations, and the iterative source removal is not valid when the detector map is warped by the Ridge. Generally, sky reconstruction is highly complicated in the case of the GC observations. To a large extent, the INTEGRAL/IBIS/ISGRI survey sensitivity is limited by systematic uncertainties, and new exposures in the GC have only minor effects on the total sensitivity.
4. Modified sky reconstruction method

The sky reconstruction method for IBIS/ISGRI should be able to split a detector image into the following layers:

- source PIFs: characterized by a flat count rate and the pattern of the projected mask;
- illumination by the Ridge: has certain low-(spatial)-frequency variations. The characteristic variations depend on the telescope orientation relative to the GP and GC;
- ISGRI background layer: contains the CXB flux and instrumental background, and has a smooth count rate.

All these layers correlate to different degrees with each other owing to the shared detector area. We modify Eq. (1) to accommodate the Ridge component \( R \):

\[
D = \sum_{i=0}^{M} f_i \text{PIF}_i + k_B B + k_R R.
\]  

The direct simultaneous solution of Eq. (2) is practically impossible before the components are orthogonalized. At first, we tried to reduce the mutual correlation between layers using different spatial features of the layers and the short list of sources. To do this, we selected \( M_b \) bright sources with \( S/N > 7 \) which appeared in the FOV. We fit the relation (2) with the modeled Ridge contribution \( R \), source PIFs, and background map \( B \). The fitting procedure was unstable, producing inadequate estimates of the layer normalizations. We noticed high uncertainty in determination of Ridge and Background map components, respectively, \( k_R \) and \( k_B \), due to its high mutual correlation.

One possible way of further disentangling the Ridge layer from others is to use different spacecraft orientations relative to the GP. To do this, we attempted to simultaneously fit the nearest \( Q \) observations (S\&W) before and after the current one:

\[
D_j = \sum_{i=0}^{M_b} f_i \text{PIF}_{i,j} + k_B B_j + k_R R_j,
\]  

where index \( j \) is running in the range \([-Q, Q]\) relative to the current observation \( j = 0 \), and \( M_b \) denotes the number of bright sources that appeared in the FOV of every \( j \in [-Q, Q] \) observations with \( S/N > 7 \). The on-axis direction of all selected observations is requested to be inside 15° radius around the position of current observation.

We fitted large data sets using Eq. (3) for different \( Q > 0 \) and found the Ridge component \( k_R \) much better constrained with respect to the other layers. Guided by the stability of the fitting procedure, we chose \( Q = 6 \) as a reasonable selection criteria. Generally, the procedure is more stable for more spatially scattered observations in the direction perpendicular to the GP. Among the available INTEGRAL observational patterns we have found that the best pattern for this approach is the Galactic Center Deep Exposure (GCDE, Core Program, see e.g. Winkler et al. 1999) and the Galactic Latitude Scans (PI Sunyaev).

The fitting procedure running on large data sets of the usual 5 × 5 pattern (see ISOC Newsletter #12, September 2004), and the Galactic Plane Scans (GPS, Core Program, see e.g. Del Santo et al. 2003; Rodriguez et al. 2003) is not as stable, but still provides valuable results.

We should note that the contribution of the \( i \)th source \( (f_i \text{PIF}_i) \) in Eq. (3) is estimated under the assumption of the constant flux \( f_i \) during the considered time interval. In a similar way, the detector background count rate \( k_B \) is also considered constant. For the chosen value of \( Q = 6 \), the maximum number of observations is 13, which is in total ~25 ks. Generally, for such a time interval, the majority of galactic X-ray sources do not vary by a factor of more than ~2, except during the outburst activity.

Actually, the modified sky reconstruction algorithm described here is used only for constraining the Ridge component and its subsequent subtraction. After this step, the IROS procedure (Sect. 2.4) is applied in the usual manner on the detector plane of the given observation (ScW).

The employed procedure still does not allow us to completely resolve the problem of highly correlated shadowgrams on the detector in the case of the GC observations, but it at least reduces the systematic residuals on mosaic images introduced by Ridge emission.

4.1. Removing systematic residuals from sky images

After removing the source shadowgrams and the background from the detector, we still see the systematic effects on sky images. These residuals can be clearly seen on deep extragalactic observations performed in staring mode when sky images are stacked (pixel-to-pixel) in detector coordinates. All systematic residuals, not visible on images of individual observations (with an exposure of ~2 ks) are amplified on the stacked image. The sky region around NGC 4151, was reconstructed with the help of the general deconvolution algorithm from the data collected in the staring mode, as shown in the left image of Fig. 8. The characteristic chessboard-like squares and ripples are clearly seen in the fully coded (central 10° × 10° square) and partially coded (outer parts) field of view.

The absence of bright sources in the field of view during these staring observations makes it clear that the presence of the patterns seen in Fig. 8 does not depend on the accuracy of our model of source shadowgram. We also cannot attribute visible systematic artifacts to the detector noisy pixels, because they were filtered out (Sect. 2.5).

The major origin of these patterns on the sky is the limited knowledge of the background pattern on the detector. It may consist of several unaccounted for parts, like the unexpected variations in pixel gains, the effective lifetimes, and lifetimes of the detector modules (the ISGRI detector has 8 modules of pixels, which in many cases change, see e.g. Fig. 5). Judging from a particular pattern of residuals on the sky, the major effect is due to the inaccurate estimate of efficiency and the energy band-passes of the detector pixels.

In the context of the general sky reconstruction method, it becomes extremely difficult to correct this problem because of the continuous degradation of detector pixels and the variation in the background environment. Despite our understanding of the origin of the residual structures on the sky, we decided to implement an alternate solution to this problem. Because the spatial scale of systematic artifacts on the sky is significantly different from the scale of the point sources, we implemented the wavelet-based image filtering procedure.

The key point of all wavelet methods is that the wavelet transform (WT) is able to distinguish structures as a function of the spatial scale, and thus is well suited to detecting small scale structures on an image embedded within larger scale features. That is why WT has been widely used for structure analysis of galaxy clusters (Slezak et al. 1994; Grebenev et al. 1995a; Rosati et al. 1995; Biviano et al. 1996; Vikhlinin et al. 1997).

In the context of an individual IBIS/ISGRI observation, we are interested in removing all large-scale structures from non-uniform sky background rather than in detecting of point
sources. The task is greatly simplified by the coded-mask aperture technique not being able to reconstruct an image of objects with a spatial size greater than the angular resolution of the telescope. For point source detection, all structures that are more extended than a point source can be safely removed. In other words, we do not need any thresholds to distinguish noise and signal, so we can remove systematic residuals with a given angular scale “as is”. In this way, the WT works as a non-parametric technique not being able to reconstruct an image of objects with a spatial size greater than the angular resolution of the telescope ART-P aboard the GRANAT mission (Grebenev et al. 1995b).

4.2. Wavelet decomposition method

To decompose a sky image, we use the à trous digital wavelet transform (DWT) algorithm because it allows easy reconstruction (Starck & Murtaugh 1994; Slezak et al. 1994; Vikhlinin et al. 1997). The method uses a kernel \( K_J = F_J - F_{J+1} \), where integer \( J \) is the so-called spatial scale index. Each \( F_J \) is constructed by five weighting coefficients \( 1, 4, 6, 4, 1/16 \) spaced by a \( 2^{-1} \) interval. Each \( F_J \) can be roughly approximated by a Gaussian of width \( 2^{J-1} \) (\( F_1 \) is a \( \delta \)-function). The convolution of an image with \( F_J \) preserves flux \( \Sigma F_J = 1, \forall J \), and convolution with \( K_J \) emphasizes the structures with the characteristic size \( \approx 2^{J-1} \) pixels, or \( 2^{J+1} \) arcmin in the case of the IBIS/ISGRI image (1 pix \( \approx 4\)'). Thus, low \( J \) values correspond to small spatial variations or high frequency, and high \( J \) reflects large spatial variations or low frequency.

On the largest scale, \( N \) the kernel \( K_N = F_N \). The original image \( I \) can be easily decomposed to its convolutions, \( W_J \) (“wavelet planes of scale \( J \)”), with kernels \( K_J \):

\[
I = \sum_{J=1}^{N} W_J.
\]

Therefore, we can consider \( W_J \) an image containing “flux” on scale \( J \), and the sum of all fluxes yields the original image. This is the basis of the wavelet decomposition algorithm. The original image is convolved with the wavelet of the first scale. The wavelet plane on the first scale is removed from the image. We then go to the next scale \( J + 1 \). In other words, we remove all small-scale features from the image before working on larger scales. That is why the small-scale features (high spatial frequency) do not affect the convolution on larger scales (at low spatial frequency). Obviously, this algorithm greatly reduces the interference of the point source with large-scale kernels.

To remove the large-scale systematic structures seen in the left image of Fig. 8, we start with a deconvolved source-free sky image of individual observation: 1) flux image is decomposed to the wavelet planes. The systematic residuals are clearly seen on scales \( J = 5, 6, 7 \). After that, we 2) restore the original image by Eq. (4) omitting these scales; and 3) return the source fluxes to the sky as described in the general reconstruction method (Krivonos et al. 2005; Goldwurm et al. 2003).

We should stress that DWT filtering is used on sky flux images, where systematic residuals are emphasized. The sky variance map was not filtered, because it only contains formal uncertainties related to the exposure time for a given sky direction.

4.3. Impact on point sources

According to the above section, the cleaning procedure operates on the source-free images, i.e. images free of catalogued sources. Therefore, DWT filtering does not directly affect the flux of known sources. However, if position of the source is unknown, its flux will not be removed from the detector before sky deconvolution, which means that source will appear on the sky. In this case, the DWT filtering will clean sky background with an embedded point source. The important question is how the implemented DWT filtering affects the flux of such a point source. The main idea is that the DWT procedure must not significantly change the point source flux.

To investigate this issue, we used standard on-axis observation of the bright source, Crab Nebula, with a total exposure of 2.7 ks. We performed DWT decomposition of the reconstructed sky image of Crab, for the range of scales 1–8. The image was then reconstructed by summing up selected wavelet scales. Crab flux was estimated on the final sky image, convolved with the effective point spread function (Krivonos et al. 2007b). Table 1 contains the measured Crab flux for the different sets of wavelet scales. The flux is expressed as a fraction relative to the flux in the original sky image. As seen from the table, \( \approx 94\% \) of the point source flux resides in the high-frequency wavelet scales 1–4, and the rest contributes to the low-frequency scales 5–8.

If we assume that the point source is significantly affected when \( \approx 5\% \) of its flux is greater than the 1\( \sigma \) survey detection

![Fig. 8. Sky region around NGC 4151 accumulated with a sequence of 95 staring observations (spacecraft orbits 74–76). The total dead-time corrected exposure is 280 ks. The angular size of each image is 30’ × 30’. The left mosaic image is obtained by the general method (Sect. 2). The image on the right was produced by summing up images of individual observations corrected with à trous wavelet decomposition algorithm (Sect. 4.1). The standard deviation of source-free pixels in the left and right images relates as 1.3 and 1.0, respectively. The new hard X-ray source IGR J11203+4531, detected during this observation is labeled in green. To illustrate how the algorithm works, we extracted the vertical profile from the green rectangular region in the left image (Fig. 10).](Image 32x643 to 153x765)

![Image 331x607 to 511x607)](Image 331x647 to 511x648)

| DWT scales, \( J \)   | Flux fraction | Significance |
|----------------------|---------------|-------------|
| 1                    | 0.00435       | 1.54        |
| 1, 2                 | 0.36121       | 127.95      |
| 1–3                  | 0.78648       | 278.60      |
| 1–4                  | 0.94208       | 333.72      |
| 1–5                  | 0.98549       | 349.09      |
| 1–6                  | 0.99647       | 352.98      |
| 1–7                  | 0.99913       | 353.92      |
| original sky image   |               |             |
| 1–8                  | 1.00000       | 354.23      |
| wavelet scales used in this work | | |
| 1–4, 8               | 0.94210       | 333.72      |
threshold, then wavelet filtering distorts only the point sources at a detection level of $> 20\sigma$. Obviously, such strong known sources are removed from the detector shadowgram before sky deconvolution, and returned to the sky image after the DWT filtering in steps 1−2. New sources detected in the survey generally have a detection significance of less than $10\sigma$. We conclude that the implemented wavelet filtering method does not affect the flux of point sources, and does not introduce significant distortion to the survey sensitivity.

### 4.4. Extragalactic sky

We performed DWT cleaning procedure (Sect. 4.2) for each observation of the already mentioned NGC 4151 staring mode campaign. The resulting image is presented in Fig. 8, to the right. It is clearly seen that all large-scale artifacts are totally removed, leaving a clean sky image. To demonstrate this improvement, we built $S/N$ distribution for pixels in the source-free sky image. The $S/N$ distribution of the original image (Fig. 8, left) is represented in Fig. 9 by the red histogram. It can be approximated by a Gaussian with $\sigma \approx 1.3$, which is consistent with the measured standard deviation of image pixels. The SNR histogram of the wavelet filtered sky image is plotted in blue. The last is well approximated by a normal distribution with a unit variance and zero mean, which means that the systematic noise has been completely removed. Assuming a normal distribution of $N = 183\,606$ pixels on a cleaned image, we expect 5 occurrences at a significance level of $1\sigma$. However, we detect 2 and 2 excesses at negative and positive values, respectively. We conclude that, for the simplified case of extragalactic observation, the DWT filtering significantly supresses (practically removes) systematic noise.

Until now, about 3 Ms of INTEGRAL exposure time has been performed in staring mode. Usually, these observations are excluded from sky mosaics owing to high systematics. By cleaning these observations with DWT we can add them to the survey.

It is interesting to note that, by averaging the archival staring observation of NGC 4151, we detected a new transient source IGR J11203+4531 at sky position RA = $11^h20^m21.60^s$, Dec = $45^\circ 31^\prime 48.0^\prime\prime$ (equinox 2000.0, uncertainty 4 arcmin). The source was found at the FOV edge where strong systematics prevented its detection before (see Figs. 8 and 10). The source is seen at $S/N = 5.3$ on the original mosaic with rms = 1.3, which gives $4\sigma$ excess. The systematics is gone on the cleaned sky, and the source has $S/N = 5.7$ on the image with rms = 1.0; i.e., the source is revealed at $5.7\sigma$. This is demonstrated by the average image profiles shown in Fig. 10. The follow-up Swift/XRT observation of IGR J11203+4531 revealed two nearby sources with coordinates RA = $11^h20^m26.92^s$, Dec = +45:34:53.77 and RA = $11^h20^m33.76^s$, Dec = +45:28:17.92 (error radii according to the “xrtcentroid” program are 5.96 and 5.31 arcsec, respectively).

### 4.5. GC region

However, we are mainly interested in improving sensitivity in the region of the GP where most of the exposures were collected. The sky image of the GP with the maximum available exposure ($\sim 20$ Ms in the GC) produced by the general reconstruction method is shown in the upper image in Fig. 11. The sky background behind the bright sources is contaminated by strong systematics, which significantly limits sensitivity for source detection. In the same data set, by taking the Galactic X-ray background into account and using DWT sky filtering, we obtain a new deep image of the GP demonstrated in the lower panel. As seen from the sky image, most of the systematic artifacts are removed, leaving a more or less uniform sky background. Obviously, the quality of the reconstructed sky is improved.

To demonstrate the efficiency of the improved reconstruction method, we built the $S/N$ distribution of the source-free $30' \times 30'$ region around the GC for general and DWT-corrected sky (Fig. 13). The $S/N$ distribution for the general sky has wide non-Gaussian lobes. The histogram representing the cleaned sky is narrow, but still far from normal distribution. This means that systematic artifacts are reduced, but still present on the sky. We measured the standard deviation of image pixels masking out bright sources. For the cleaned and general sky, standard deviation relates as $1.33/1.84$, which gives us the total sensitivity improvement of $\sim 28\%$. After taking out the irreducible Poisson statistics with unit standard deviation, the suppression of systematic noise in the $\sim 20$ Ms deep field of the GC region is $\sim 44\%$.

### 5. Survey

For our analysis we used all data publicly available in July 2009 and observations performed as a part of the GRXE study program (PI Sunyaev). The latter is mainly based on the Russian quota of INTEGRAL observing time. The sky image of any individual observation was produced by the modified sky reconstruction method described in this work. The obtained sky images were added to the all-sky mosaics covering the whole sky.

The survey coverage area is shown in Fig. 12. We calculated a fraction of the sky area covered by the survey at nominal and effective sensitivity. In the first case, the sensitivity is essentially the detection threshold, estimated from actual exposure. The effective sensitivity was estimated by multiplying the nominal error map by variances of local background. The limiting flux and sensitivity for 10% and 90% of the sky coverage are summarized in Table 2.

**General sky reconstruction method:** the survey’s limiting flux for the longest exposure is $\sim 35\%$ higher than nominal.
Table 2. Survey limiting flux in mCrabs for source detection at the 5σ significance level (17–60 keV, 1 mCrab = 1.43 × 10^{-11} erg s^{-1} cm^{-2}).

| Category   | Nominal | Gen. method | Mod. method |
|------------|---------|-------------|-------------|
| Lim. flux  | 0.26    | 0.35        | 0.33        |
| 10% sky    | 0.60    | 0.70        | 0.63        |
| 90% sky    | 4.32    | 5.00        | 4.32        |

For a large coverage area at high limiting flux, which is typical of high-latitude observations, the effective sensitivity is ~15% lower than expected.

Modified sky reconstruction method: the survey effective coverage is apparently closer to the nominal. In the region of low limiting flux, the effective sensitivity is ~27% worse than nominal. The sky coverage at high flux is consistent with what is expected from an actual exposure, i.e. Poisson statistics.

In Fig. 14 we show survey sensitivity as a function of exposure time. Generally, the survey sensitivity grows with exposure by T^{-1/2} as expected. The region of high exposure in the GC is noticeable by its reduced sensitivity in contrast to extragalactic observations where the limiting flux is expected to follow pure statistics. Again, the survey sensitivity of the modified method is closer to a nominal sensitivity.

6. Conclusion

We presented the improved sky reconstruction method for the IBIS telescope, which suppresses the systematic effects. First, the method considers extended Galactic X-ray ridge emission that strongly affects the background illumination of the ISGRI detector. Second, we applied a non-parametric (model-free) background approximation based on an à trous wavelet decomposition. The wavelet cleaning was naturally integrated into the sky reconstruction process with the main advantage that we knew exactly what we were filtering out without distorting the original sky flux. The overall systematic noise in the ~20 Ms deep field of the GC was reduced by ~44%, thereby improving the the total sensitivity of observations by ~28%. The reconstructed sky images of high galactic latitude fields were practically free of systematic residuals, and the sensitivity was consistent with what is expected from Poisson statistics.

Most of the INTEGRAL observing time was spent in the GP and GC, giving us the possibility of conducting the most sensitive survey ever made of the Milky Way above 20 keV. The minimal detectable flux with a 5σ detection level reached the level of 3.7 × 10^{-12} erg s^{-1} cm^{-2}, which is ~0.26 mCrab in the 17–60 keV energy band. The survey covered 90% of the sky down to the flux limit of 6.2 × 10^{-11} erg s^{-1} cm^{-2} (~4.32 mCrab) and 10% of the sky area down to the flux limit of
Fig. 11. Map of the sky region near the GP obtained with IBIS/ISGRI in the 17–60 keV energy band. The total exposure is about 20 Ms in the GC region. Upper panel: sky mosaic acquired by the general sky reconstruction method (see Sect. 2). Lower panel: sky mosaic produced by an improved reconstruction algorithm (Sect. 4). The corresponding S/N distributions of pixels in a 30° × 30° region around the GC are shown in Fig. 13.

Fig. 12. Fraction of the sky surveyed as a function of the limiting flux for source detection with 5σ significance. The black curve demonstrates sky coverage for nominal sensitivity. The effective sensitivity estimated for general and modified sky reconstruction methods are shown by the red and blue curves, respectively (see Sect. 5).

Fig. 13. Distribution of formal pixel significance in a 30° × 30° region around the GC (Fig. 11). For plot description see Fig. 9.
sensitivity measured in (and out of) sky region variations in the field of each 20° × 20° and red points are 5σ sensitivity versus exposure:

\[
\frac{\sigma}{\text{corrected exposure time}} = \frac{0.77 \times (T/\text{Ms})^{-1/2}}{10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}}.
\]

The top and bottom panels demonstrate the fit to the nominal sensitivity taking into account background variations in each 20° × 20° sky projection (Sect. 5). The sensitivity measured in (and out of) sky region |b| < 20° and |b| > 15° is shown in red (green).

8.6 × 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} (~0.60 \text{ mCrab}). A catalog of sources detected in the survey is presented in the paper by Krivonos et al. (2010).

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References

Barthelmy, S. D., Barbier, L. M., Cummings, J. R., et al. 2005, Space Sci. Rev., 120, 143
Bassani, L., Molina, M., Malizia, A., et al. 2006, ApJ, 636, L65
Bazzano, A., Stephen, J. B., Fiocchi, M., et al. 2006, ApJ, 649, L9
Bockmann, V., Soldi, S., Ricci, C., et al. 2009, A&A, 505, 417
Bird, A. J., Barlow, E. J., Bassani, L., et al. 2004, ApJ, 607, L33
Bird, A. J., Barlow, E. J., Bassani, L., et al. 2006, ApJ, 636, 765
Bird, A. J., Malizia, A., Bazzano, A., et al. 2007, ApJS, 170, 175
Bird, A. J., Bazzano, A., Bassani, L., et al. 2010, ApJS, 186, 1
Biviano, A., Durret, F., Gerbal, D., et al. 1996, A&A, 311, 95
Cusumerano, G., La Parola, V., Segreto, A., et al. 2010, A&A, 510, A48
Del Santo, M., Rodriguez, J., Ubertini, P., et al. 2003, A&A, 411, L369
Dwek, E., Arendt, R. G., Hauser, M. G., et al. 1995, ApJ, 445, 716
Eckart, D., Produit, N., Pahani, S., Neronov, A., & Courvoisier, T. J.-L. 2008, A&A, 479, 27
Fenimore, E. E., & Cannon, T. M. 1978, ApJ, 17, 337
Fenimore, E. E., & Cannon, T. M. 1981, Appl. Opt., 20, 1858
Gehrels, N., Chincarini, G., Giommi, P., et al. 2004, ApJ, 611, 1005
Goldwurm, A., David, P., Froshnit, L., et al. 2003, A&A, 411, L223
Grebenev, S. A., Forman, W., Jones, C., & Murray, S. 1995a, ApJ, 445, 607
Grebenev, S. A., Pavlinsky, M. N., & Sunyaev, R. A. 1995, Proc. of the Workshop, Imaging in High Energy Astronomy, held in Anacapri, Sept. 26–30, 1994, ed. L. Bassani, & G. di Cocco (Dordrecht: Kluwer Academic Publishers), 155
Krivonos, R., Vikhlinin, A., Churazov, E., et al. 2005, ApJ, 625, 89
Krivonos, R., Revnivtsev, M., Churazov, E., et al. 2007a, A&A, 463, 957
Krivonos, R., Revnivtsev, M., Lutovinov, A., et al. 2007b, A&A, 475, 775
Krivonos, R., Tsygankov, S., Revnivtsev, M., et al. 2010, A&A, in press
Lebrun, F. 2005, IEEE Transactions on Nuclear Science, 52, 3119
Molkov, S. V., Cherepashchuk, A. M., Latovinov, A. A., et al. 2004, AstL, 30, 534
Reglero, V., Sánchez, F., Rodríguez, J., et al. 2001, ESASP, 459, 619
Revnivtsev, M. G., Sazonov, S. Y., Gilfanov, M. R., & Sunyaev, R. A. 2003, Astron. Lett., 29, 587
Revnivtsev, M., Sunyaev, R., Varshalovich, D., et al. 2004, Astron. Lett., 30, 382
Revnivtsev, M. G., Sazonov, S. Y., Molkov, S. V., et al. 2006a, Astron. Lett., 32, 145
Revnivtsev, M., Sazonov, S., Gilfanov, M., Churazov, E., & Sunyaev, R. 2006b, A&A, 452, 169
Rodriguez, J., Del Santo, M., Lebrun, F., et al. 2003, A&A, 411, L373
Rosati, P., della Ceca, R., Burg, R., Norman, C., & Giacconi, R. 1995, ApJ, 445, L11
Sazonov, S., Revnivtsev, M., Krivonos, R., Churazov, E., & Sunyaev, R. 2007, A&A, 462, 57
Skinner, G. K., Ponman, T. J., Hammersley, A. P., & Eyles, C. J. 1987, Astroph. Sp. Sci., 136, 337
Starck, J. L., & Murtagh, F. 1994, A&AS, 100, 10
Stickel, F., & Gerhal, D. 1994, A&AS, 100, 10
Stark, J. L., & Murtagh, F. 1994, A&AS, 100, 10
Tueller, J., Baumgartner, W. H., Markwardt, C. B., et al. 2010, ApJS, 186, 378
Ubertini, P., Lebrun, F., Di Cocco, G., et al. 2003, A&A, 411, L11
Vikhlinin, A., Forman, W., & Jones, C. 1997, ApJ, 474, L7
Winkler, C., Gehrels, N., Lund, N., Schönfelder, V., & Ubertini, P. 1999, Astrophys. Lett. Commun., 39, 361
Winkler, C., Courvoisier, T. J.-L., Di Cocco, G., et al. 2003, A&A, 411, L1
Worrall, D. M., Marshall, F. E., Boldt, E. A., & Swank, J. H. 1982, ApJ, 255, 111

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