

## First results from the INTEGRAL galactic plane scans<sup>★</sup>

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**Abstract.** Scans of the Galactic plane performed at regular intervals constitute a key element of the guaranteed time observations of the INTEGRAL observing programme. These scans are done for two reasons: frequent monitoring of the Galactic plane in order to detect transient sources, and time resolved mapping of the Galactic plane in continuum and diffuse line emission. This paper describes first results obtained from the Galactic plane scans executed so far during the early phase (Dec. 2002–May 2003) of the nominal mission.

**Key words.** compact objects – high energy transients – nucleosynthesis

### 1. Introduction

The Core Programme (CP) of guaranteed time observations (Winkler 2001) during the first year of INTEGRAL's nominal mission consists of a deep exposure of the central Galactic radian (GCDE), regular scans of the Galactic plane (GPS) and pointed observations. A total observing time of 9.3 Ms – corresponding to 35% of the observing time available during the first year – has been allocated to CP observations, out of which 2.3 Ms have been reserved for regular scans of the Galactic plane (GPS) using INTEGRAL's three high-energy

instruments: the spectrometer SPI (Vedrenne et al. 2003), the imager IBIS (Ubertini et al. 2003) and the X-ray monitor JEM-X (Lund et al. 2003).

The GPS are mainly done for two reasons: the most important one is to provide frequent monitoring of the Galactic plane in order to detect transient sources, because the gamma-ray sky in the INTEGRAL energy range is dominated by the extreme variability of many sources as demonstrated by previous X- and gamma-ray missions. The scans would find sources in high state (outburst) which warrant possible scientifically important follow-up (Target of Opportunity) observations. The second reason is to build up time-resolved maps of the Galactic plane in continuum and diffuse line emission such as <sup>26</sup>Al, <sup>44</sup>Ti and 511 keV with modest exposure. CGRO and SIGMA detected Galactic compact sources of several different categories/groups which include X-ray binaries (e.g. X-ray novae, Be binary pulsars) and in particular the so-called microquasars

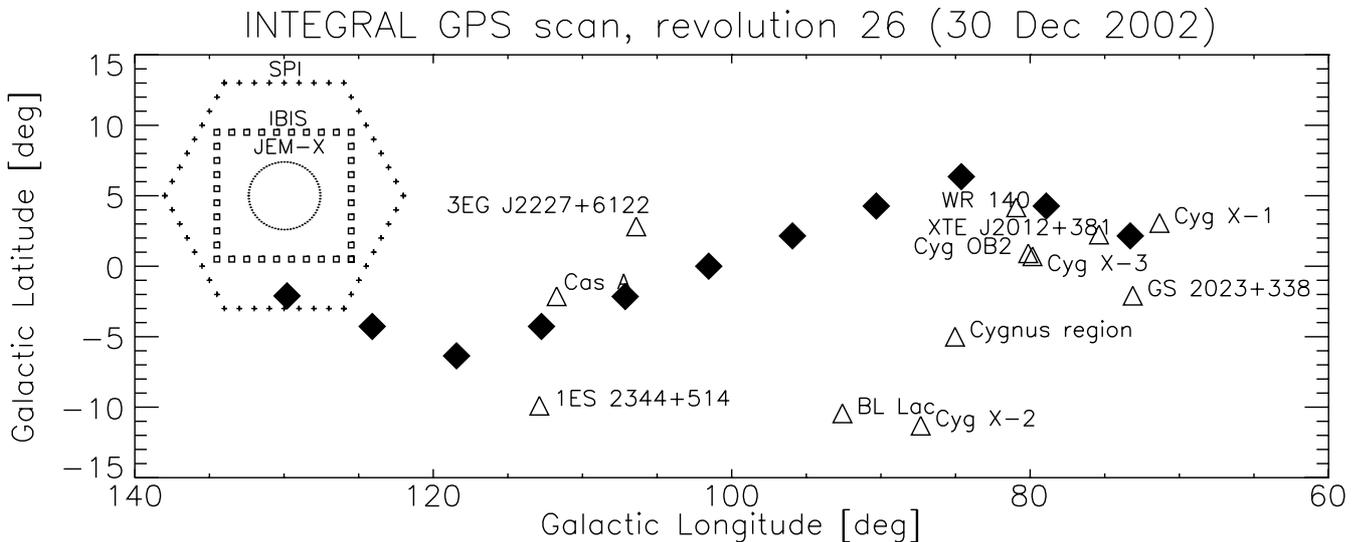
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**Table 1.** Journal of Galactic plane scans, executed during early mission phase.

Exposure <sup>a</sup> [s]	Start	End	# Pointings	Start ( <i>l, b</i> ) [deg]	Stop ( <i>l, b</i> ) [deg]
24 200	28-Dec.-02	28-Dec.-02	11	128.3, 2.1	71.9, 6.4
24 200	30-Dec.-02	30-Dec.-02	11	73.3, 2.1	129.8, -2.1
33 000	11-Jan.-03	14-Jan.-03	15	270.0, -2.1	123.4, 2.1
28 600	29-Jan.-03	29-Jan.-03	13	337.0, 4.3	269.3, 4.3
59 400	02-Mar.-03	03-Mar.-03	27	325.0, -2.1	189.6, -2.1
110 000	12-Mar.-03	16-Mar.-03	50	54.6, 0.0	99.9, 4.3
123 200	24-Mar.-03	29-Mar.-03	56	295.5, 4.3	110.4, -2.1
92 400	05-Apr.-03	08-Apr.-03	42	273.3, -2.1	339.8, -2.1
83 600	17-Apr.-03	20-Apr.-03	38	108.9, 2.1	278.1, -2.1
66 000	28-Apr.-03	02-May-03	30	209.6, 4.3	102.5, -2.1
26 400	13-May-03	14-May-03	12	226.0, 0.0	288.1, -2.1
28 600	22-May-03	23-May-03	13	123.7, 2.1	56.0, 2.1

<sup>a</sup> Note that the scheduled exposure is shown. Actual exposures obtained for IBIS and JEM-X during this period amounts to ~95% and to ~75% for SPI, due to telemetry constraints during the early mission phase.

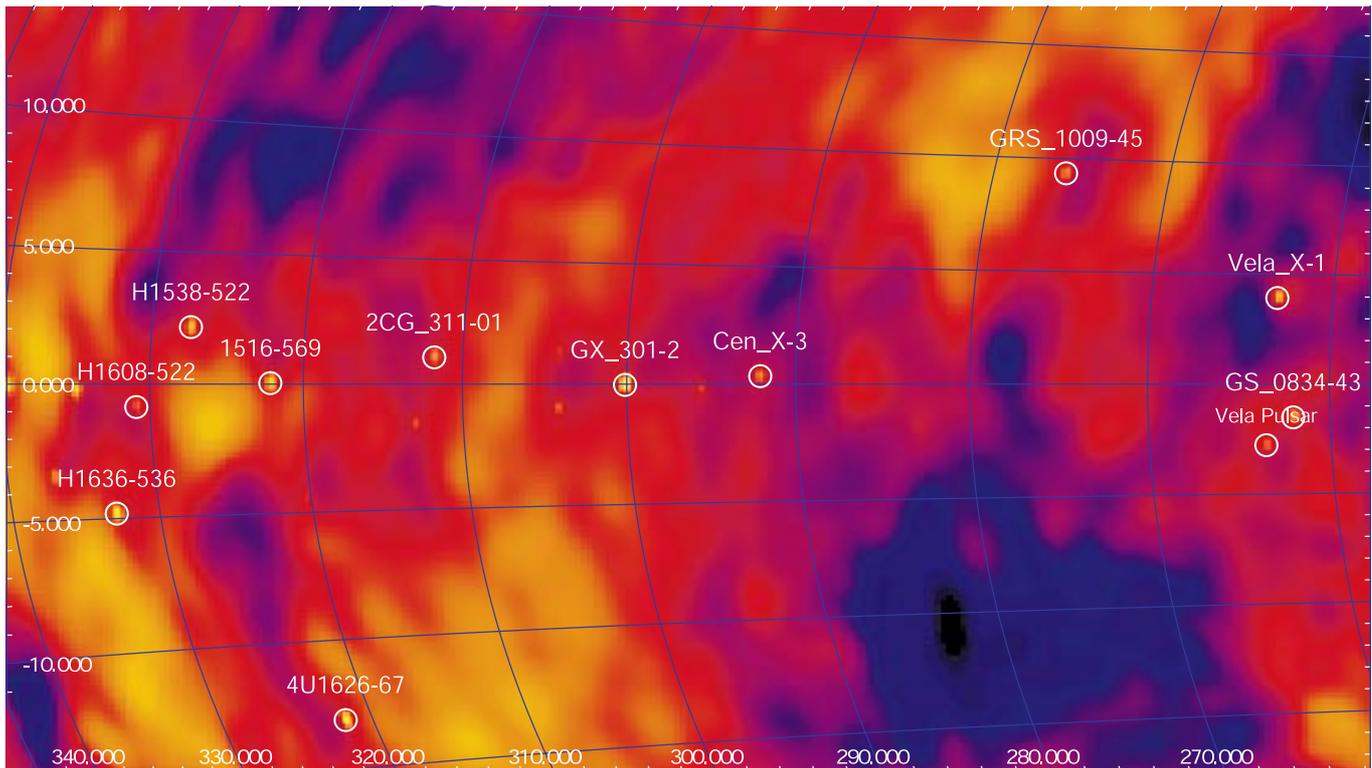


**Fig. 1.** Pointings of the “sawtooth-shaped” GPS scan (filled symbols) as performed during revolution 26 (30 Dec. 2002). The fully coded fields of view (FCFOV, SPI: 16°, IBIS: 9° × 9°, JEM-X: 5°), and some known high energy targets are shown for illustration.

GRS 1915+105 and GRO J1655–40. The pre-launch estimate on the occurrence rates for events that INTEGRAL can observe is about 2 events/year for each of these event classes which include: (i) X-ray novae (including systems with black hole and with neutron star primaries), (ii) Be pulsar outbursts, (iii) AGN flares, and (iv) Novae and Supernovae. The pointing constraints due to the fixed solar arrays of the INTEGRAL spacecraft (Jensen et al. 2003) have been taken into account in the estimate. The important time scales for the transient outbursts vary significantly from class to class and from event to event, but a typical duration of an event is 1–2 weeks and a typical variability time scale is of the order of 1 day.

The scans occur once per 4 revolutions (i.e. every 12 days) by performing a “slew – and stare” manoeuvre of the spacecraft along the visible (accessible) part of the Galactic plane with latitude extent  $\pm 10^\circ$ . A “revolution” corresponds to the duration (~3 days) which INTEGRAL needs to complete one orbit. The accessible part of the Galactic plane depends on

viewing constraints including the  $40^\circ$  solar aspect angle due to the fixed solar arrays. The angular distance between subsequent exposures (2200 s each) along the scan path is  $6^\circ$ . The scans are performed as a “sawtooth” (Fig. 1) with inclination of  $21^\circ$  with respect to the Galactic plane, each subsequent scan is shifted by  $27.5^\circ$  in galactic longitude. The sawtooth patterns build up a grid of various dither pointings, facilitating the imaging analysis for SPI. The visibility of the Galactic plane depends on the annual season. On average a strip of width  $b = \pm 10^\circ$  has a longitude extent of  $170^\circ$  (ranging from  $110^\circ$  to  $360^\circ$ ) and requires on average 21 hours of scanning (ranging from 12 hours to 42 hours) which includes the total of exposures and spacecraft slews. In this paper we describe preliminary results obtained from GPS scans during the early mission phase from December 2002 to May 2003 concentrating on the monitoring of known and the detection of new point sources. The GPS scans executed during the early phase of the mission are shown in Table 1.



**Fig. 2.** Example of a SPI significance (*Spiros*) sky map in galactic coordinates, (20–40 keV), obtained during GPS scans in the period December 2002–March 2003.

## 2. First results from SPI

Two analysis tools have been developed for SPI (Vedrenne et al. 2003) to analyse gamma-ray sources: *Spiros* (Skinner & Connell 2003), which is specialized for point sources, and *Spiskymax* (Strong 2003) which is aimed more at diffuse emission but also images point sources. *Spiros* uses an input catalogue and tests each source for significance and flux. It also searches for sources in addition to those in the catalogue.

The number of known sources found at significance level  $>5\sigma$  by *Spiros* for all scans during revolutions 25–67 (December 2002–May 2003) in the energy range (20–40) keV (using data from 234 pointings and 538 ks exposure) is 33, three yet unknown sources were found which need further study. Well-known and bright sources are clearly detected in the short GPS exposures; the status of the less significant sources has to be investigated in detail on a source-by-source basis. The same applies to the 3 sources found which were not in the input catalogue.

For SPI an important use of the GPS will be to extend the core programme’s deep exposure (4.3 Ms) of the Galactic Centre (GCDE) to the entire Galactic plane for large-scale mapping. Already with 6 months data the plane coverage is almost complete, although at lower exposure than the GCDE. It enables the first sky maps of the whole plane to be made. Figure 2 shows a SPI significance skymap from the GPS derived using *Spiros* in the (20–40) keV energy band. The bright sources detected during GPS are visible.

Another important scientific objective for SPI is to search for transient line features like those discovered by SIGMA

from Nova Muscae in 1991 (Goldwurm et al. 1993) and from 1E1740.7–294 in 1990 (Bouchet et al. 1991; Sunyaev et al. 1991) and in 1992 (Cordier et al. 1993). Broad, transient features ( $FWHM \sim 50\text{--}250$  keV) centered between 350 keV and 500 keV were observed on timescales of  $\sim$  hours to days.

We have estimated the SPI sensitivity to such events during a single GPS scan; depending on the source position, two or three consecutive GPS pointings (2200 s each) can be used. Table 2 lists calculated SPI sensitivities for the transient features based on quoted line centroid and  $FWHM$ . Reported fluxes are shown for comparison. We show two sets of estimated SPI sensitivities, one for optimum source location in the path of the GPS scan, and one for an intermediate case. Of course, the larger the distance of the source from the GPS scan path, the lower the sensitivity. The sensitivity estimates are based on single-detector events only (“SE+PE”) using background measured during revolutions 11–45 (Nov. 2002–Feb. 2003). The mask opacity is approximated at 50%, and we assume perfect background knowledge (i.e. background uncertainty only from measurement statistics), and assume no other significant sources in the relevant energy band in the FOV.

## 3. First results from IBIS

IBIS (Ubertini et al. 2003) was designed as a gamma-ray wide field of view telescope with high sensitivity even for short observing time of the order of a few thousand seconds. This characteristic was optimised with the scientific goal to regularly monitor a large fraction of the Galactic plane and to discover

**Table 2.** SPI estimated sensitivities (during one GPS scan) to broadened line features at (350–500) keV as observed by SIGMA.

Reference	Line Position [keV]	Line <i>FWHM</i> [keV]	SPI sensitivity (optimum) [ph/(cm <sup>2</sup> s)]	SPI sensitivity (intermed.) [ph/(cm <sup>2</sup> s)]	Observed Flux [ph/(cm <sup>2</sup> s)]
<i>IE1740.7 – Oct. 1990 event</i>					
Bouchet et al. (1991)	480	240	$7.7 \times 10^{-3}$	$10 \times 10^{-3}$	$13 \times 10^{-3}$
Sunyaev et al. (1991)	410	180	$6.2 \times 10^{-3}$	$8.4 \times 10^{-3}$	$(9.5 \pm 4.5) \times 10^{-3}$
<i>IE1740.7 – Sep. 1992 event</i>					
Cordier et al. (1993)	350	170	$5.5 \times 10^{-3}$	$7.5 \times 10^{-3}$	$4.3^{+2.7}_{-1.5} \times 10^{-3}$
<i>IE1740.7 – Oct. 1990 + Sep. 1992 events</i>					
Cordier et al. (1993)	390	190	$6.5 \times 10^{-3}$	$8.8 \times 10^{-3}$	
<i>Nova Muscae – Jan. 1991 event</i>					
Goldwurm et al. (1993)	481	54	$3.9 \times 10^{-3}$	$5.3 \times 10^{-3}$	$(6.0 \pm 2.9) \times 10^{-3}$

**Table 3.** New INTEGRAL sources<sup>a</sup>.

Source	Flux (mCrab) (15–40) keV	Flux (mCrab) (40–100) keV	Reference
IGR J18483–0311	10 ( <i>S/N</i> ~ 21)	5 ( <i>S/N</i> ~ 11)	2 May 2003 (ATEL 157)
IGR J17597–2201	5 ( <i>S/N</i> ~ 10)	10 ( <i>S/N</i> > 14)	30 Apr. 2003 (ATEL 155)
IGR J18325–0756	10	5	28 Apr. 2003 (ATEL #154)
IGR J18539+0727	20	20	21 Apr. 2003 (ATEL #151)
IGR J17091–3624	–	20	19 Apr. 2003 (ATEL #149)
IGR J17464–3213	60	60	28 Mar. 2003 (ATEL #132)
IGR J16358–4726	50	20	19 Mar. 2003 (IAUC #8097)
IGR J19140+098	50–100		6 Mar. 2003 (IAUC #8088)
IGR J16320–4751	10–50		1 Feb. 2003 (IAUC #8076)
IGR J16318–4848	50–100		29 Jan. 2003 (IAUC #8063)

<sup>a</sup> All IGR sources were discovered during core programme observations (3 sources during GPS, 5 sources during GCDE), except IGR J16320–4751 and IGR J19140+098 which were detected during open time pointed observations.

most of the expected transient sources, whose existence was anticipated by X–Ray mission like BeppoSAX and RXTE, operating at lower energies. During the first part of the CP observation a sensitivity of about 20 mCrab at 50 keV has been achieved for the GPS scan, combining together different pointings of the same sky region within the FOV.

So far almost 100 known sources have been detected, including all persistent though variable LMXB and HMXB and several different flaring or out–bursting sources with intensity above 20–50 mCrab. As anticipated most of them are Neutron Star systems, either weakly or strongly magnetised and a few are Black Hole candidates. At the same time 10 new INTEGRAL sources have been discovered (see Table 3) by the IBIS low energy detector ISGRI.

Most of them show substantial emission in the lower energy range (15–40) keV, and, even if showing a relatively soft spectrum (cf. IGR J16358–4726), few very hard ones have sustained emission up to (150–200) keV (cf. IGR J17464–3213). Others show an unusually high intrinsic absorption (cf. IGR J16318–4848) up to  $2 \times 10^{24} N_H$  suggesting the existence of a new class of Galactic objects. They appear to be enshrouded by a dense envelope and visible only above (5–10) keV (Revnivtsev et al. 2003; Matt & Guainazzi 2003;

Walter et al. 2003), which puts them at the limit of CHANDRA and XMM–Newton capabilities, and amenable to deep investigations with IBIS.

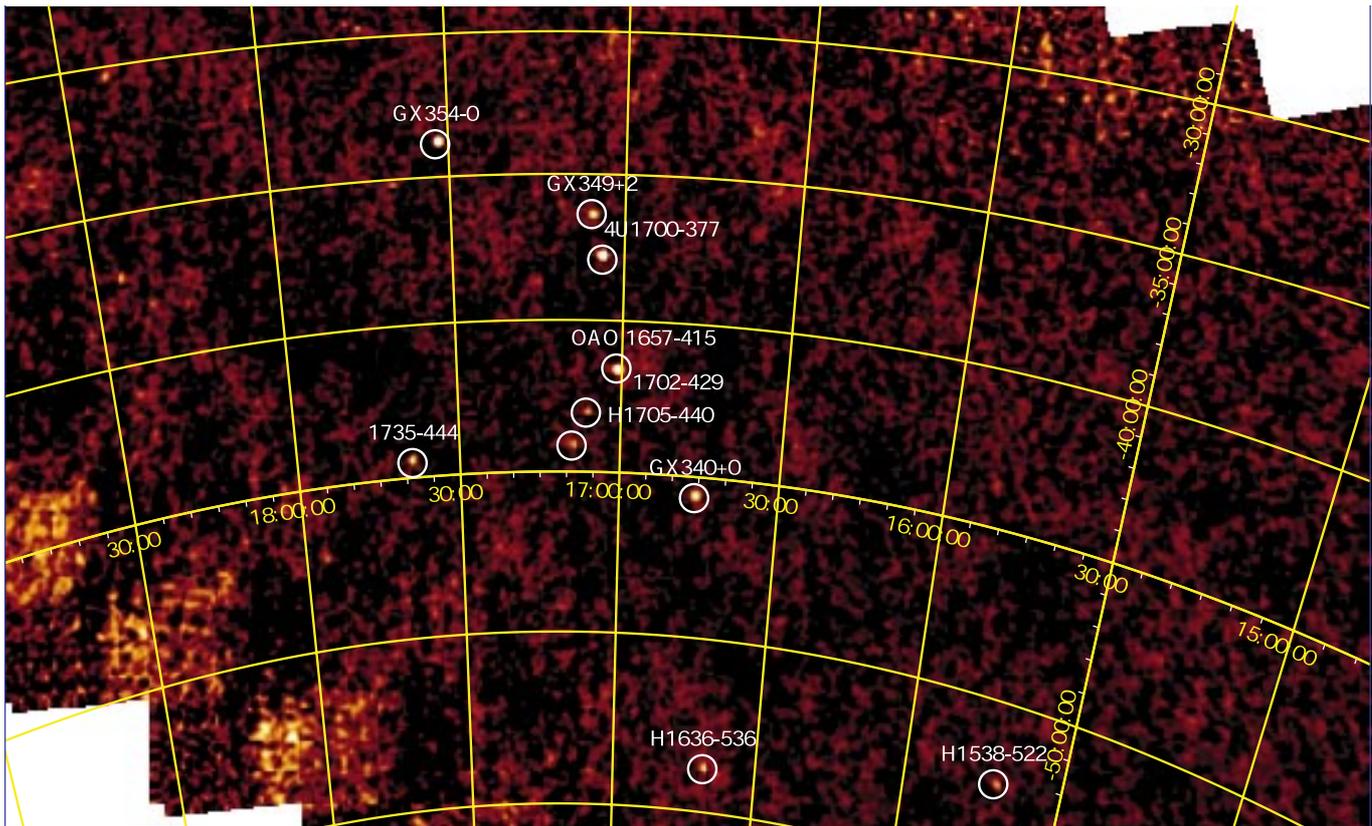
As an example of a GPS scan obtained by IBIS, Fig. 3 was obtained by IBIS/ISGRI during revolution 50 (12 March 2003), energy range (15–30) keV.

#### 4. First results from JEM–X

During the GPS scans executed during the first half of 2003 JEM–X detected more than 50 known sources, most of them galactic X–ray binaries. We also recorded numerous X–ray bursts. Most of the sources had fluxes in excess of 20 mCrab. However, sources down to 3 mCrab have been detected.

Figure 4 shows a (3–15) keV sky map close to the Galactic Centre, obtained during the GPS on 24 March 2003. Six pointings of 2200 s each have been combined into a mosaic using the overall exposure and a map of the vignetting function to determine weights of summed pixels.

So far, JEM–X has not detected a bona fide transient source which was confirmed by independent observations. This may not be surprising, given the more restricted (partially coded) field of view (10° diameter) compared to the IBIS partially coded FOV of 29° × 29°. One of the INTEGRAL



**Fig. 3.** Sky map (equatorial J2000 coordinates) obtained by IBIS/ISGRI (15–30) keV, during Galactic plane scan on 12 March 2003.

transients, IGR J17464–3213, was, however, detected a number of times after the initial discovery by IBIS. For this source, a HEAO source, H1743–322, which had its last outburst in 1977, detected by IBIS on 2003, Mar. 21 (Revnitsev et al. 2003a), JEM–X could confirm a VLA–radio counterpart (Rupen et al. 2003) near the edge of the original IBIS error box as the true origin of the X-ray signal (Fig. 5).

The JEM–X source detection software is still developing, and we expect eventually to reach a detection threshold around 5 mCrab in a single GPS pointing of 2200 s. Given that the angular separation between the GPS pointings is comparable to the JEM–X FOV, we will frequently get the opportunity to observe a given source in only one GPS pointing. To achieve a reliable identification of transient sources it will therefore be very beneficial to get both JEM–X units operating in parallel – at the present time only one JEM–X is active, pending the conclusion of the investigation of a long term drift of the gas gain of JEM–X2 discussed elsewhere in this volume (Brandt et al. 2003).

## 5. Outlook

In this section the sensitivities achieved to date during GPS observations are presented in Table 4 and used to predict the scientific return expected from future scans. For sensitivities, we consider individual GPS scans with exposure per point of 2200 s. These are the sensitivities relevant for transient detection and analysis. The sensitivities are based on actual source detections achieved since launch. The IBIS number is

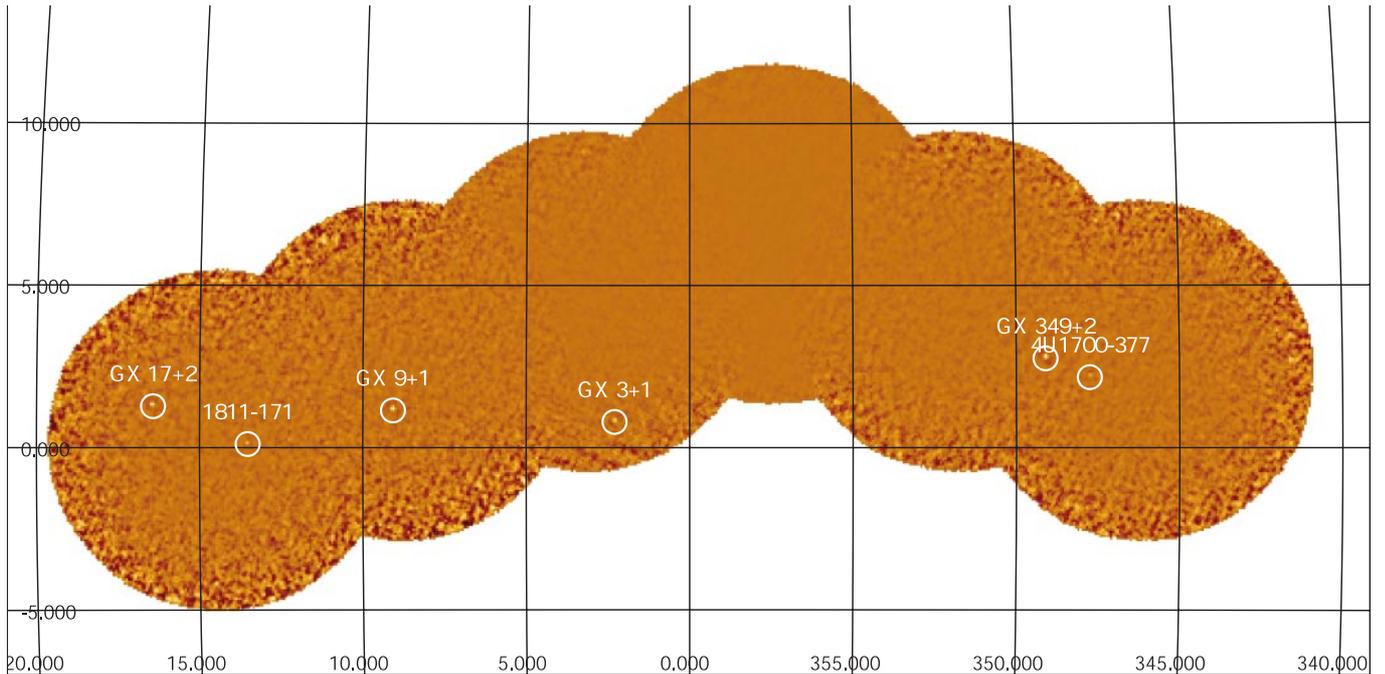
**Table 4.** Sensitivities achieved during GPS observations (see text).

Instrument	$\Delta E$ [keV]	$5\sigma$ Sensitivity [mCrab]	Exposure [ksec]
IBIS	15–40	36	2.2
SPI	20–40	62	6.6
JEM–X	5–20	20	2.2

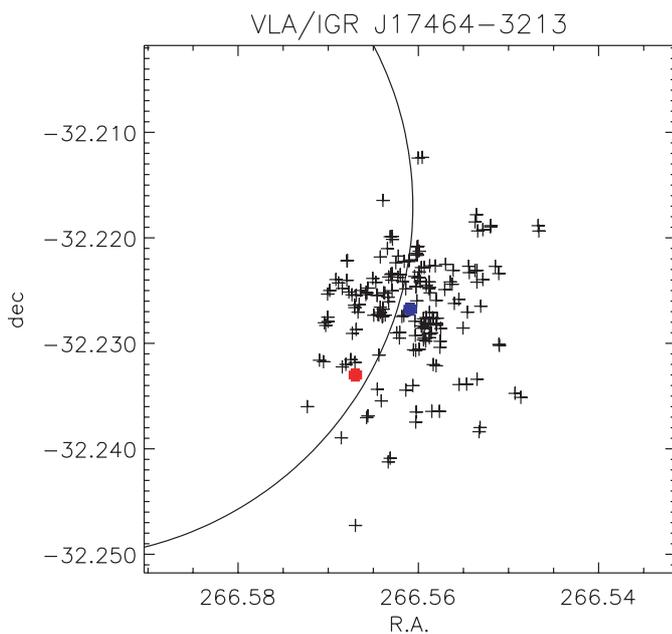
for the low–energy ISGRI portion of the response and relevant for single pointings (2200 s) in a scan, including systematic errors. JEM–X is also quoted for single pointings. For SPI, with its wide field of view, the sensitivity is derived from analysis of sources seen in a single GPS scan: a source is seen  $\sim 3$  times in a scan, hence the average exposure is  $\sim 6600$  s, depending on the source position with respect to the scan path.

For transient science, studies before launch gave a prediction of  $\sim 10$  transients detected per year by INTEGRAL. This was based on an estimated sensitivity threshold of  $\sim 20$  mCrab. The classes of objects considered were: (i) X–ray novae (including systems with black hole and with neutron star primaries), (ii) Be pulsar outbursts, (iii) AGN flares, and (iv) Novae and Supernovae.

One of the great successes of the INTEGRAL mission to date has indeed been its discovery of new transient sources (see Table 3). Ten new sources have been found over a period of about 4 months, giving a discovery rate of more than 2 per month. Most of those sources have been found during core programme observations, mostly during GCDE



**Fig. 4.** JEM-X sky map (3–15 keV) of a GPS (24 March 2003) close to the Galactic Centre, see text.



**Fig. 5.** Original IBIS location error circle, counterpart suggested by VLA observations (red dot) and JEM-X positions obtained from many pointings and energy bands (black crosses). The JEM-X data confirm the association of the radio and the hard X-ray source. The blue dot marks the centroid of the JEM-X positions. A residual uncorrected error in the JEM-X alignment is evident.

observations which have dominated the core programme time so far. Combining the GCDE exposures which are clustered twice per year because of the visibility of the Galactic Centre region, and the once-per-12-day GPS scans, it is expected that a rate of 10–20 transient discoveries per year will be obtained.

The range of uncertainty is due to not knowing which of the new sources are steady and which are transient.

For mapping science with SPI, the time spent on GPS scans to date (i.e. until May 2003: 282 pointings with a total of 643 ks observing time) has not yet been long enough to build sufficient statistics for diffuse continuum and line studies. However, when this number grows to  $\sim 100$  ks per GPS pointing at the end of the first year for SPI, it will be possible to start making maps of the full plane. The results from this should give sensitivities comparable to those achieved in prime locations of the plane by the COMPTEL instrument on CGRO. If such scans are continued over a 5 year extended mission for INTEGRAL, the exposure per point will become 0.5 Ms. The result will be a beautiful map of the plane showing the sites of nucleosynthesis in the Galaxy over the past million years.

## 6. Conclusions

The Galactic plane scans of INTEGRAL's core observing programme, executed so far during the early mission phase, have proven to be of fundamental importance for the science return of the mission. INTEGRAL is demonstrating its unique capability to routinely monitor the Galactic plane with large field of view and excellent sensitivity. The number of new sources found so far is very encouraging. The prospects of detecting transient line features and producing maps in the light of diffuse continuum and line emission are very promising. The present structure of the core programme of INTEGRAL will in principle continue during the future operational lifetime.

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