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The INTEGRAL[*] Burst Alert System

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Abstract. We describe the INTEGRAL Burst Alert System (IBAS): the automatic software for the rapid distribution of the coordinates of the Gamma-Ray Bursts detected by INTEGRAL. IBAS is implemented as a ground based system, working on the near-real time telemetry stream. During the first six months of operations, six GRB have been detected in the field of view of the INTEGRAL instruments and localized by IBAS. Positions with an accuracy of a few arcminutes are currently distributed by IBAS to the community for follow-up observations within a few tens of seconds of the event.

Key words. gamma rays: bursts

1. Introduction

For many years after their serendipitous discovery, Gamma-Ray Bursts (GRB) were relegated as a puzzling phenomenon in the field of high-energy astronomy. The real breakthrough in their understanding came with the discovery of X–ray (Costa et al. 1997), optical (van Paradijs et al. 1997), and radio (Frail et al. 1997) afterglows. This finally allowed to set a distance scale, proving that at least long (>2 s) GRB are located at cosmological distances and associated to the final evolutionary stages of massive stars (Stanek et al. 2003; Hjorth et al. 2003). These findings led to a renewed interest and to enormous developments in this field during the last few years (see, e.g., van Paradijs et al. 2000).

It is clear that the rapid derivation and distribution of accurate sky positions for GRB is crucial to successfully carry out such studies. Satellite missions specifically devoted to this, such as *HETE-2* (Ricker et al. 2003) and *Swift* (Gehrels 2001) have in fact been developed. Although INTEGRAL is a general γ-ray astronomy mission, not particularly optimized for GRB studies, it was soon realized that the unprecedented imaging performances of its IBIS instrument (Ubertini et al. 2003) could offer the possibility of rapid localization of the events observed by chance in its large field of view. It was therefore

proposed to implement a "burst alert system" in order to allow rapid multi-wavelength follow-ups (Pedersen et al. 1997).

Compared to previous and current GRB localization facilities, IBAS represents a step forward. Error regions at the arcmin level were obtained by *BeppoSAX* (Costa 2000) with typical delays of one hour or more, related to the frequency (once per 96 min orbit) of the ground contacts. The Inter Planetary Network (IPN, Hurley et al. 2001) can provide error regions of a few tens of square arcmin, but after several hours (or even days). Real time localizations from CGRO/BATSE were distributed in the past with Bacodine (now called GCN, Barthelmy et al. 2001), but their typical uncertainty was of a few degrees. Currently, very nice results are being obtained with *HETE-2* (Ricker et al. 2003). The GRB positions derived on-board at the ~degree level are available within a few seconds, and later (1–2 hours) refined down to a few arcmin, with a ground analysis.

A great advantage of the INTEGRAL mission is the continuous contact with the ground stations during the observations, made possible by its high orbit (3 days period). As shown below, IBAS is currently able to provide small error regions (~4′ radius) within few tens of seconds from the GRB.

2. IBAS description

2.1. Overall architecture

The INTEGRAL Burst Alert System (IBAS) is the automatic software devoted to the rapid detection and localization of GRB (Mereghetti et al. 2001b). Contrary to most other γ-ray astronomy satellites, no on-board GRB triggering system is present

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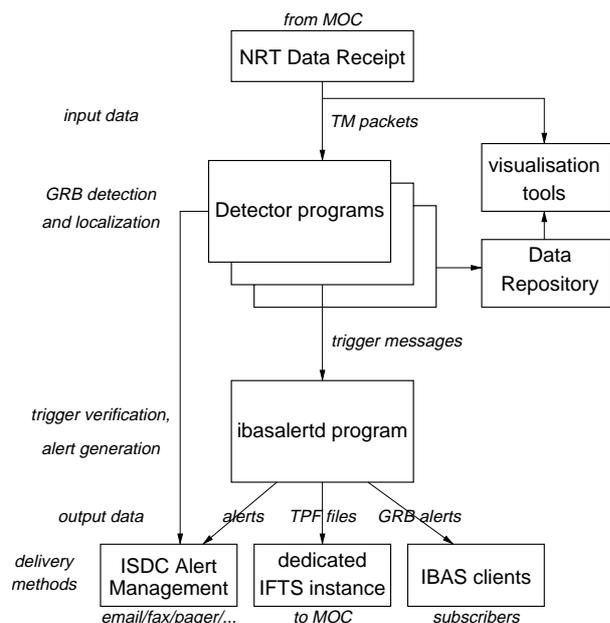
Fig. 1. Main components an interfaces of the IBAS software.

on INTEGRAL. Since the data are continuously transmitted without important delays, the search for GRB is done at the INTEGRAL Science Data Centre (ISDC, Courvoisier et al. 2003). The fact that IBAS is running on ground has some advantages: besides the availability of a larger computing power, a very important factor is the greater flexibility for what concerns software and hardware upgrades, with respect to systems operating on board satellites. To take full advantage of this flexibility, the IBAS software architecture has been designed in a modular way, which allows to plug-in various programs for the GRB search, based on different instruments and algorithms.

Figure 1 gives an overview of the IBAS software architecture. The telemetry, received at the ESA Mission Operation Center (MOC) in Darmstadt, is continuously transmitted to the ISDC on a 128 kbs dedicated line. As soon as the data reach the ISDC, they are processed by the Near Real Time Data Receipt Subsystem which extracts the relevant telemetry packets and, after some basics checks, feeds them into IBAS. IBAS comprises several independent *Detector Programs* runing in parallel. They have the task to trigger on possible GRB and to perform preliminary checks to filter out, as much as possible, spurious events. This architecture allows us to use in parallel different methods for the GRB detection, as well as to run several instances of the same *Detector Program* with different parameter settings (e.g. timescales, energy cuts, etc.) in order to increase the sensitivity for GRB with different properties.

Currently, programs based on two different algorithms using data from the ISGRI/IBIS detector are in use, plus one program to detect GRB seen by the anticoincidence shield of SPI (in this case no directional information is available). Other *Detector Programs* based on data from JEM-X and SPI are under development.

The trigger messages produced by the *Detector Programs* are then analyzed by the *Ibasalertd* program which combines them in order to extract the maximum information to decide on

the reality of the GRB. The details of the logic of trigger confirmation can be defined in a very flexible way by means of a set of parameters involving significance of detection, tolerance for positional and temporal coincidence, etc. The *Ibasalertd* program also converts detector coordinates to sky positions based on the best available attitude information, verifies that the triggers are not due to known variable sources, and eventually distributes via Internet an *IBAS Alert Packet* containing the position of the GRB. When several trigger messages, received at slightly different times, refer to the same GRB, they are filtered by *Ibasalertd* in order to distribute new *Alerts Packets* only if relevant new information is available (e.g. an improved localization).

All the IBAS processes are multi-thread applications written in C or C++. They run as daemon processes, which means that they do not perform any terminal input/output and run in background. IBAS processes perform several subtasks in parallel, each one handled by a separate thread. With some unavoidable exception, the subtasks are independent and do not block each other.

As can be seen in Fig. 1, IBAS also comprises visualization and analysis tools which can be used for off-line examination of the data. In order to minimize the reaction time, the off-line analysis is based on data products directly saved by the IBAS programs.

Finally, all the IBAS programs interface with the ISDC Alert Management System, which is used by the ISDC operators and scientists on duty to monitor the correct functioning of the software and to react to possible problems and/or interesting scientific events.

2.2. Detector programs

Among the INTEGRAL instruments, IBIS is the most appropriate for GRB localization, thanks to its large field of view ($29° \times 29°$) and its capability to locate sources at the arcminute level (Gros et al. 2003). As mentioned above, IBAS localizations are based on two different programs using the data from the IBIS lower energy detector ISGRI (Lebrun et al. 2003).

Since imaging analysis is the most time consuming part of the algorithm, the first program performs a simple monitoring of the overall ISGRI counting rate. This is done by looking for significant excesses with respect to a running average, in a way similar to traditional triggering algorithms used on-board previous satellites. Different instances of this program are currently running with trigger timescales ranging from 2 ms to 5.12 s. The imaging analysis is done only when a significant counting rate excess is detected. Images are accumulated for different time intervals, deconvolved with very fast algorithms, and compared to the pre-burst reference images in order to detect the appearance of the GRB as a new source. This step is essential to eliminate many triggers due to instrumental effects and background variations which do not produce a point source excess in the reconstructed sky images.

The algorithm used in the second *Detector Program* is entirely based on image comparison. Images of the sky are continuously produced and compared with the previous ones to

search for new sources. With respect to the other program, this one has the advantage of being less affected by variability of the background or of other sources in the field of view. Currently, this program is sampling timescales from 10 to 40 s.

Finally a third kind of *Detector Program* is used to search for GRB detected by the Anti Coincidence System (ACS) of the SPI instrument. The available data consist of light curves with the overall ACS count rate binned at 50 ms resolution (von Kienlin et al. 2003a). Although no directional information is available, the resulting triggers can in principle be used by the *Ibasalertd* program to confirm low significance events seen in other instruments.

## 2.3. Distribution of the IBAS Alert Packets

IBAS *Alert Packets* with the GRB information are sent via Internet, using the UDP transport protocol. Each packet is 400 bytes long, and consists of several fields, the format and content of which is explained in detail in the documentation available at the ISDC web pages[1]. Different types of *Alert Packets* are distributed. Users can select which type(s) they want receive. Users interested in receiving the IBAS *Alert Packets* can also download a *Client Software*, written in standard C language and tested on the most popular operating systems, that allows them to receive the *Alert Packets* and to easily use their content, e.g. in the software commanding robot telescopes.

IBAS can send more than one packet for each GRB. After the first one (WAKEUP type) distributed with the shortest delay, one or more packets of type REFINED are sent automatically if a more precise localization becomes available. Finally, one or more packets of type OFFLINE can be sent manually after the interactive analysis of the data.

Since automated telescopes can exploit the a priori knowledge of the INTEGRAL pointing direction (e.g. to reduce the slew time in case of a GRB alert, to obtain reference images of the pre-GRB sky, to monitor the counterparts of INTEGRAL targets), IBAS is also sending packets containing updated pointing information each time a slew to a new direction begins. Test *Alert Packets* of each type are sent every 6 hours, to allow the IBAS users to check their software.

2.4. Automatic reconfiguration of the Optical Monitor Camera

INTEGRAL also carries an Optical Monitor Camera (OMC, Mas-Hesse et al. 2003), which consists of a 50 mm telescope covering the central $5° \times 5°$ region of the IBIS and SPI field of view. During normal operations, owing to the limited telemetry rate allocated to the OMC, only the data from a number of small pre-selected windows around sources of interest are recorded and transmitted to the ground. The *Ibasalertd Program* checks whether the derived GRB position falls within the OMC field of view. In such a case, the appropriate telecommand with the definition of a new window centered on the interesting region is generated and sent to the MOC to be uploaded to the satellite.
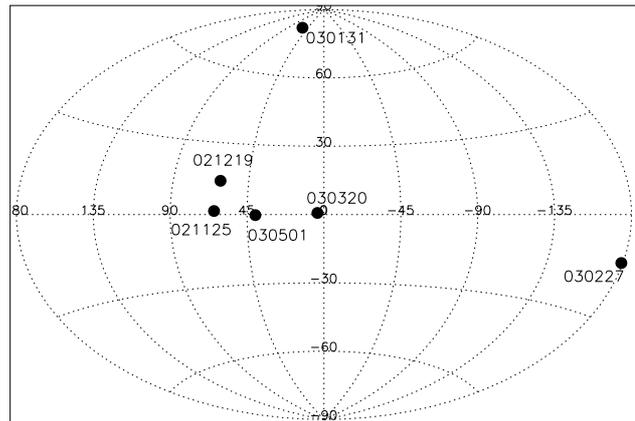
Fig. 2. Positions in Galactic coordinates of the six GRB localized so far by INTEGRAL. The large fraction of GRB at low Galactic latitudes reflects the non-uniform sky exposure obtained by INTEGRAL during the first months of the mission.

This will allow to quickly observe the GRB/afterglow emission in the optical band. The OMC observation will consist of several frames with integration times of 60 s to permit variability studies and to increase the sensitivity for very intense but short outbursts. The expected limiting magnitude is of the order of $V \sim 14$ for an integration time of 60 s at high Galactic latitudes.

3. IBAS performances

The IBAS programs have been running almost continuously since the launch of the INTEGRAL satellite. The first two months of operations were devoted to the setting of the many parameters involved in the GRB detection. Some changes in the algorithms were also required to adapt them to the in-flight data characteristics. Delivery of the *Alert Packets* to the external clients started on January 17, 2003. Since then it has always been enabled, except for the period from February 12 to 28 (during calibration observations of the Crab Nebula), and for a short interruption (4 hours) on April 23 (for hardware maintenance reasons).

Six GRB have been discovered to date in the field of view of IBIS (see Table 1 and Figs. 2 and 3). When a GRB is detected by IBAS with high significance, the *Alert Packet* with the corresponding coordinates is automatically delivered to all subscribed users. This actually happened so far only for GRB 030501. It would have also occurred for GRB 021219 and GRB 030227, but, as mentioned above, they were detected while the external delivery of alerts was switched off.

Possible GRB detected by IBAS with lower significance generate alerts reaching only the members of the IBAS Team, who quickly perform an analysis of the relevant data. If the GRB is confirmed an *Alert Packet* of type OFFLINE with the derived position is then distributed. This occurred for GRB 030131 and GRB 030320.

IBAS has also distributed a number of alerts which were subsequently found to be unrelated to GRB. They were retracted by OFFLINE packets and GCN circulars typically within a few tens of minutes. These false alerts had
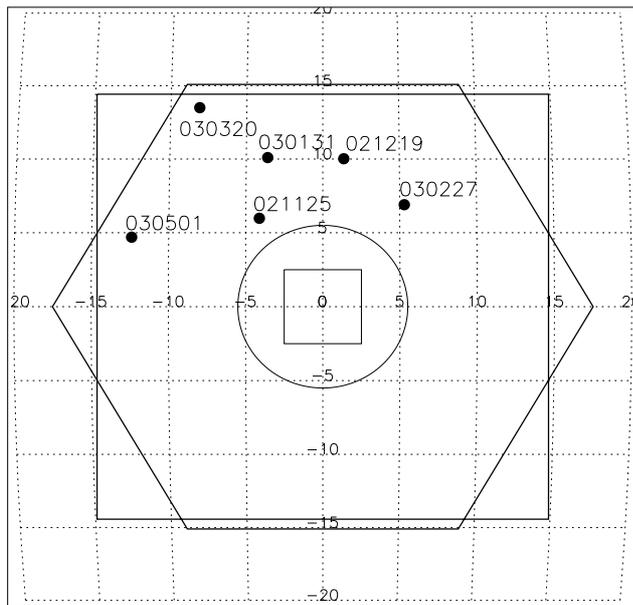
Table 1. GRB in the IBIS Field of view.

GRB	Duration [s]	Delay[a] in position distribution internal/public	External delivery of IBAS *Alert Packets*	Peak Flux (20–200 keV) [ph cm^{-2}s^{-1}]	Peak Flux (20–200 keV) [erg cm^{-2}s^{-1}]	Fluence (20–200 keV) [erg cm^{-2}]	Ref.[b]
021125	25	–[c] / 0.9 days	OFF	22	2×10^{-6}	7.4×10^{-6}	1, 2
021219	6	10 s / 5 hr	OFF	3.7	3.5×10^{-7}	9×10^{-7}	3, 4
030131	150	21 s / 2 hr[d]	ON	1.9	1.7×10^{-7}	7×10^{-6}	5, 6
030227	20	35 s / 48 min	OFF	1.1	1.6×10^{-7}	7.5×10^{-7}	7, 8
030320	50	12 s / 6 hr	ON	5.7	5.4×10^{-7}	1.1×10^{-5}	9, 10
030501	40	30 s / 30 s	ON	2.7	3×10^{-7}	3×10^{-6}	11, 12

[a] Computed from the beginning of the GRB.

[b] References (for the first announcement and the first journal publication only): (1) Bazzano & Paizis (2002), (2) Malaguti et al. (2003), (3) Mereghetti et al. (2002), (4) Mereghetti et al. (2003d), (5) Borkowski et al. (2003), (6) Götz et al. (2003a), (7) Götz et al. (2003b), (8) Mereghetti et al. (2003a), (9) Mereghetti et al. (2003b), (10) von Kienlin et al. (2003b), (11) Mereghetti et al. (2003c), (12) Beckmann et al. (2003).

[c] The IBAS *Detector Programs* were in idle mode owing to the limited telemetry allocation for IBIS/ISGRI during this observation. See Ref. 2 for details.

[d] The localization of this GRB was complicated by the fact that it was detected while the satellite was performing a slew between two pointings. This also reduced its significance level below the threshold for immediate alert distribution. See Fig. 5 for the resulting error regions.

Fig. 3. Positions of the six GRB in the field of view of the INTEGRAL instruments: IBIS (large square), SPI (hexagon), JEM-X (circle) and OMC (small square). The scale is in degrees.

different origins. Each of them led to appropriate changes in the *Ibasalertd* input parameters and/or to modifications of the software in order to fix the problem. Most of the false alerts were caused by an unlucky combination of a very bright source in the field of view and some unexpected problem in the instruments and/or ground segment. In fact, bright (and/or variable) sources are not a problem for IBAS under normal conditions: all the triggers are cross-checked with a list of sky positions of known bright sources before being distributed. Obviously, this filter does not work if the wrong source coordinates are computed. To date this happened a few times, either because

the imaging analysis failed due to some unexpected data configuration related to the instrument or because a wrong satellite attitude[2] was used to convert from instrumental to celestial coordinates.

Although in these months we have made considerable progress in the IBAS reliability, unexpected situations are by their nature difficult to deal with a priori and might generate other false alerts in the future. IBAS users have the possibility of trading off between speed of reaction time and reliability of the event by subscribing only to particular types of *Alert Packets*.

3.1. Time delay

The time performances of IBAS for what concerns the GRB detected so far are summarized in Table 1.

The time delay in the distribution of coordinates results from the sum of several factors. First of all there is a delay on board the satellite. This is variable and depends on the instrument. In the case of IBIS/ISGRI data the average delay is about 5 s, but it can be much longer for other instruments (e.g. approximately 20 s on average for the SPI ACS data, up to one minute for JEM-X data). Signal propagation to the ground station is negligible (maximum ~0.6 s), but some time is required before the data are received at the ISDC passing through the MOC. This is on average 3 s when the ESA ground station in Redu (Belgium) is used, or 6 s when the NASA Goldstone ground station is used.

[2] Specifically, problems arise whenever the satellite does not follow the planned timeline (e.g. due to a telecommand which failed or during manual recommanding). Since the attitude data from the star trackers are transmitted to the ISDC with a delay of a few minutes, IBAS must use the attitude predicted from the timeline whenever a trigger occurs shortly after the slew (i.e. about every hour, due to the dithering mode of observation).
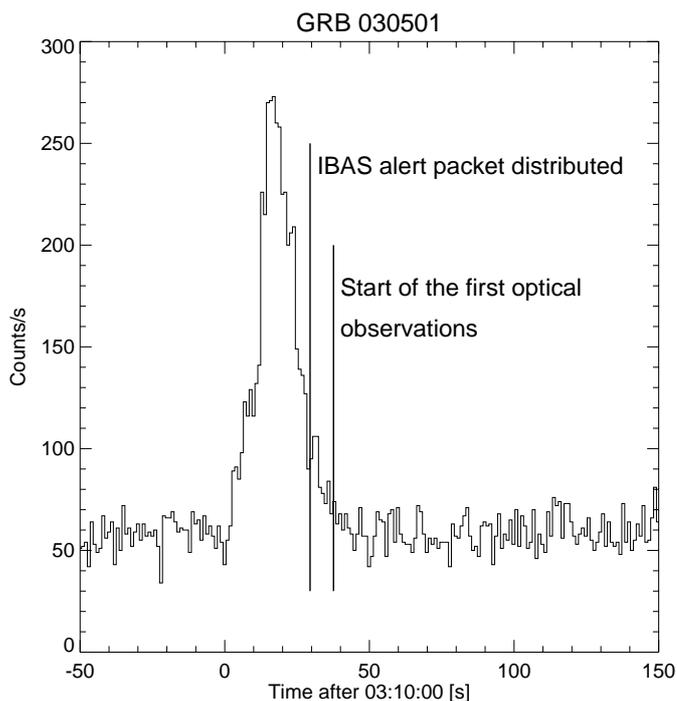
Fig. 4. Time performance of IBAS in the localization of GRB 030501, the GRB with the fastest positioning to date. The IBIS/ISGRI light curve refers to the 20–200 keV range. The two vertical lines indicate the time at which IBAS distributed the position with an error radius of 4.4′ and the start of the first observation of the field obtained with the TAROT automatic telescope (Boer & Klotz 2003).

The time to detect the GRB depends on the algorithm which triggers. The delay between the trigger time and the GRB onset is of course dependent on the intensity and time profile of the event. The IBAS simultaneous sampling in different timescales should ensure a minimum delay in most cases, however in practice a minimum of ~5 s is required to accumulate an image with sufficient statistics.

Finally, the conversion to sky coordinates, comparison with list of known variable sources, *Alert Packet* construction and delivery require less than about 2 s. Of course, the above numbers assume nominal condition, i.e. no telemetry gaps, no saturation of the allocated telemetry, no missing auxiliary data files, etc.

Thus, in many cases, we foresee to be able to generate alerts while the GRB is still ongoing. Indeed this has happened for GRB 030501, whose position with an uncertainty of only 4.4′ reached all the IBAS users only 30 s after the beginning of the GRB (Fig. 4). To our knowledge, such a combination of high speed and small error region was never achieved before in the localization of a GRB. Unfortunately, this GRB was located at low Galactic latitude in a region of very high interstellar absorption which prevented sensitive searches for counterparts (see Fig. 2).

3.2. Location accuracy

The source location accuracy (SLA) of coded mask imaging systems depends on the intrinsic angular resolution of the instrument and on the signal to noise ratio of the source. For sources detected with a high statistical significance the SLA can be a small fraction of the angular resolution. The angular resolution of IBIS/ISGRI is ~12′, but sources are typically located with an uncertainty of ~1–2′. For sources detected with a signal to noise ratio of ~30, the SLA is smaller than 30″ (90% confidence level).

For most of the time (except, e.g., during satellite slews) the INTEGRAL attitude accuracy is smaller than a few arcseconds (Walter et al. 2003). However, based on the data collected so far, it turns out that the current uncertainties in the relative alignment between the instruments and the satellite reference frame, lead to some differences between the derived and true positions of known sources. These differences depend on the position in the field of view, increasing at large off-axis angles. For IBIS/ISGRI these values range from 15″ on-axis to ~2.4′ at the border of the field of view.

For this reason, a conservative systematic error of 4′ is currently added in quadrature to the statistical error in the GRB positions distributed in the automatically delivered *Alert Packets*. Usually a better accuracy is obtained with the off-line analysis.

Figure 5 summarizes the performance in terms of localization accuracy obtained so far. Note that at the beginning of the mission the in-flight instrument misalignment was not calibrated yet. Therefore, error radii as large as 20′ or 30′ were given. The error regions obtained with the IPN, and the coordinates of the optical transients discovered for the two GRB for which prompt observations could be done, are also shown in the figure. Their agreement with the INTEGRAL positions confirms that the IBAS localizations are correct.

3.3. Sensitivity

The sensitivity of the IBIS/ISGRI detector is very close to that estimated before the INTEGRAL launch (Ubertini et al. 2003). Based on such expected sensitivity, we predicted a rate of GRB localizations with IBAS of about one per month (Mereghetti et al. 2001a), which seems to be confirmed by the results obtained so far.

A rough evaluation of the sensitivity to GRB can be derived as follows. The typical IBIS/ISGRI overall count rate in the energy range 15–200 keV used by one of the IBAS *Detector Programs* varies between about 400 and 800 counts s^{-1}, depending on the background conditions and on the presence of bright sources in the field of view. For a trigger time interval of 1 s and the current threshold value, a minimum net count rate of 120–170 counts s^{-1} is required to trigger (and to produce enough counts to locate the position in the deconvolved image). Assuming a typical GRB spectrum, such a count rate corresponds to a flux of ~0.14–0.22 photons cm^{-2} s^{-1} (20−200 keV). This applies to the central 9° × 9° of the IBIS field of view, where the full instrument effective area can be used. In the external part of the field of view, the so called partially coded region, the sensitivity is worse. This explains why the GRB discovered so far have relatively high peak fluxes compared to the above sensitivity (see Table 1 and Fig. 3).
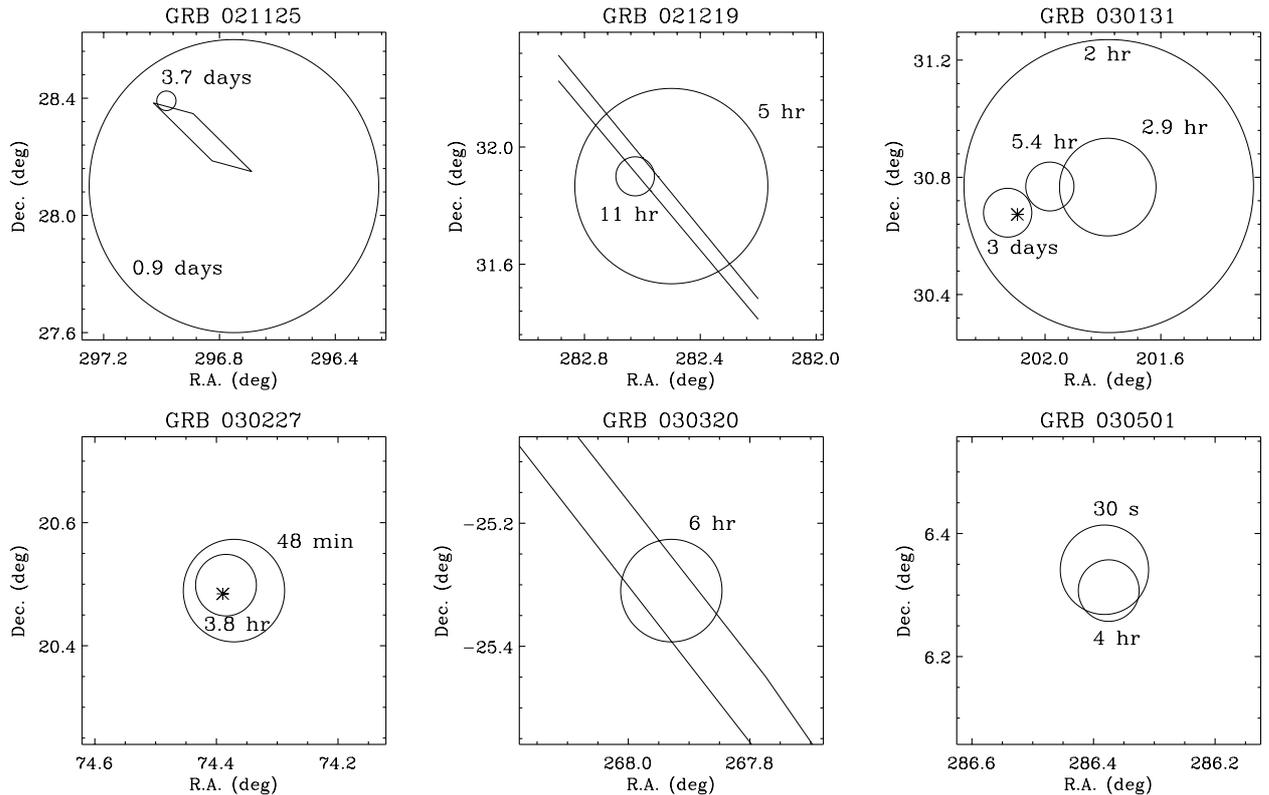
Fig. 5. Error regions distributed for the six GRB in the field of view of the INTEGRAL instruments, with the corresponding delays. Note the different scale of the three upper ($1° \times 1°$) and lower ($0.5° \times 0.5°$) panels. The parallelogram and the straight lines indicate error regions independently derived with the IPN (Hurley et al. 2002a; Hurley et al. 2002b; Hurley et al. 2003). The asterisks indicate the positions of the optical transients associated to GRB 030131 (Fox et al. 2003) and GRB 030227 (Castro-Tirado et al. 2003).

4. Conclusions

The results obtained in the first months of the INTEGRAL mission demonstrate that IBAS is working as expected. It can provide GRB positions with an accuracy of a few arcmin within few tens of seconds, at a rate of about one GRB per month. In addition, IBAS is distributing the light curves of about one GRB per day detected with the SPI ACS (von Kienlin et al. 2003a). These can be used to locate the bursts which are observed also by other satellites of the IPN.

It is remarkable that, after only two months from the start of in orbit operation of the instruments, IBAS was already functioning successfully, as demonstrated by the localization of GRB 021219. The results presented here, as summarized in Fig. 5 and Table 1, indicate that the IBAS capabilities, in terms of positional accuracy and speed of localization, have improved during the last few months. Although the location in the Galactic plane prevented deep studies of some of the IBAS GRB, successful observations of optical and X–ray afterglows have been obtained for GRB 030131 (Götz et al. 2003a) and GRB 030227 (Mereghetti et al. 2003a; Castro-Tirado et al. 2003).

It is expected that, as more experience is gained with the data and triggering algorithms, as well as by adding new *Detector Programs* using data from the other INTEGRAL instruments, the IBAS performances will improve also in terms of rate of GRB localizations.

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Letter to the Editor