Real time localization of Gamma Ray Bursts with INTEGRAL

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ABSTRACT

The INTEGRAL satellite has been successfully launched in October 2002 and has recently started its operational phase. The INTEGRAL Burst Alert System (IBAS) will distribute in real time the coordinates of the GRBs detected with INTEGRAL. After a brief introduction on the INTEGRAL instruments, we describe the main IBAS characteristics and report on the initial results. During the initial performance and verification phase of the INTEGRAL mission, which lasted about two months, two GRBs have been localized with accuracy of $\sim 2$-4 arcmin. These observations have allowed us to validate the IBAS software, which is now expected to provide quick (few seconds delay) and precise (few arcmin) localization for $\sim 10$-15 GRBs per year.

THE INTEGRAL MISSION

INTEGRAL is a satellite of the European Space Agency devoted to high-resolution imaging and spectroscopy in the hard X-ray / soft $\gamma$-ray energy range (Winkler et al 1999). After a very successful launch from the Baikonur Cosmodrome in Kazakhstan by a Russian Proton rocket on October 17, 2002, INTEGRAL has been injected into a three day period orbit with perigee of $\sim 9,000$ km and apogee of $\sim 153,000$ km. Thanks to this highly eccentric orbit, the satellite spends most of the time outside the Earth radiation belts, where it can carry out long, uninterrupted observations.

The INTEGRAL spacecraft carries two main instruments operating in the $\sim 15$ keV – 10 MeV energy range. They are optimized respectively for spectroscopy (SPI, Vedrenne et al. 1999) and imaging (IBIS, Ubertini et al. 1999) performances. Both are able to obtain images of the $\gamma$-ray sky using the coded aperture technique.

SPI is based on an array of 19 Germanium detectors cooled to 85 K to provide an energy resolution of $\sim 2$ keV at 1 MeV. It has a wide field of view (diameter $\sim 30^\circ$) and an angular resolution of $\sim 2^\circ$, adequate for a detailed mapping of the diffuse line emission in the Galactic plane.

Since IBIS is the instrument more relevant for the accurate localization of GRBs, we will describe it in more detail. IBIS has been optimized for the imaging performances by means of a coded mask, made of square tungsten elements with a thickness of 15 mm, placed at a distance of $\sim 3$ m from the detection plane.

The mask, that accounts for about one third of the total IBIS weight ($\sim 650$ kg), absorbs $\sim 70\%$ of the photons at 1.5 MeV, in correspondence of its closed elements, while the mask mechanical support retains an adequate transparency at low energy for the open elements. The good contrast of the coded aperture pattern is in fact directly related to the instrument sensitivity. The size of the mask elements yields an angular resolution of 12 arcmin, unprecedented at the energies covered by IBIS, and appropriate to resolve...
sources in crowded regions, such as the Galactic Bulge. The IBIS field of view is very large: \( \sim 29^\circ \times 29^\circ \) (at zero response), and with a uniform sensitivity within its central part (\( \sim 10^\circ \times 10^\circ \)).

In order to effectively cover an extended energy range, the IBIS detection plane is composed of two layers with different characteristics and based on different technologies. The top layer, ISGRI (Lebrun et al. 2001), consists of an array of 128\( \times \)128 Cadmium Telluride (CdTe) square pixels (4 mm \( \times \) 4 mm each). It covers the energy range from \( \sim 15 \) keV up to a few hundreds keV with a total sensitive area of \( \sim 2600 \) cm\(^2\). The CdTe is a semiconductor that can be used at ambient temperature providing a good energy resolution (\( \sim 7\% \) at 100 keV) without the need of complex cooling systems. ISGRI is used in “photon” mode, i.e. the complete information of each detected event (position, energy and arrival time) is recorded and transmitted to the ground.

Due to the CdTe thickness of 2 mm, the ISGRI detection plane becomes almost transparent for photons above \( \sim 200 \) keV, but such photons will be efficiently stopped by PICsIT, the second layer of the instrument. PICsIT is based on an array of 64\( \times \)64 scintillators of Caesium Iodide doped with Thallium (CsI(Tl)). Each element is a small bar of CsI(Tl) with dimensions 8.6\( \times \)8.6\( \times \)30 mm\(^3\) coupled with a photodiode. Although the two IBIS layers are in principle operating as independent imaging systems, their data will be used in a combined analysis to better study the spectral properties of the observed sources over the whole energy range. In addition, a fraction of the detected photons will undergo a Compton interaction in ISGRI, before being detected by PICsIT. For such “Compton” events, the energy and position measurements provided by the two layers (which are separated by \( \sim 10 \) cm), will give some constraints on the possible arrival directions, allowing to increase the signal to noise ratio by appropriate selections aimed at excluding directions not modulated by the mask aperture or not compatible with the position of the source of interest.

The two main INTEGRAL instruments, SPI and IBIS, are complemented by an X-ray monitor (JEM-X, 4-35 keV) and an optical camera (OMC) operating in the V band. All the INTEGRAL instruments are co-aligned and will be used simultaneously to provide a broad energy coverage of the targets in the central part of the IBIS and SPI field of view.

**INTEGRAL AND GRBs**

Although the INTEGRAL satellite was not specifically conceived as a mission devoted to GRBs studies, it was soon realized that the excellent imaging performances of IBIS 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. Such a proposal was boosted by the results obtained with the BeppoSAX satellite that clearly demonstrated the excellent capabilities of coded mask instruments to quickly detect and locate GRBs.

Accurate estimates based on the LogN-LogS relations for GRBs derived from BATSE led to a predicted rate of at least one GRB per month in the IBIS field of view (Mereghetti et al. 2001a), for which positions at the arcmin level can be obtained. Note that the source location accuracy and the angular resolution, though related, are two different concepts. Although the IBIS angular resolution (i.e. the width of the point response function) is 12 arcmin, sources can be located with a much better accuracy, which is a function of the signal to noise ratio. For instance, a source with a signal to noise ratio of 30 can be located by ISGRI with an accuracy of 30″ (90% c.l.).

Exploiting the continuous telemetry downlink of the INTEGRAL satellite, it was decided to carry out the search for GRBs on ground, at the INTEGRAL Science Data Center (ISDC, Couvoisier et al. 1999). The ISGRI data normally reach the ISDC within a few seconds from their detection on board the satellite. When a GRB is detected, its coordinates are automatically distributed via internet to the subscribed clients.

**THE INTEGRAL BURST ALERT SYSTEM**

The INTEGRAL Burst Alert System (IBAS) is the automatic software running at the ISDC for the rapid detection and localization of GRBs (Mereghetti et al. 2001b). In order to optimize the response time, IBAS is independent of the main data processing pipeline of the ISDC.

Fig. 1 gives an overview of the IBAS software architecture. The telemetry, received at the ESA Mission Operation Center in Darmstadt, is continuously transmitted to the ISDC on a 128 kbs dedicated line, where the Near Real Time Data Receipt subsystem extracts the relevant telemetry packets and, after some basics
checks, feeds them into the IBAS subsystem. IBAS basically consists of several *Detector Programs* and the *Ibasalertd Program*. All these programs run in parallel. The *Detector Programs* have the task to trigger on possible GRBs and to perform preliminary checks to filter out, as much as possible, spurious events. The *Ibasalertd* program has the task to further filter the triggers, by combining in an appropriate way the information from the different *Detector* programs, and to eventually send out the GRB Alerts. 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.

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 GRBs with different properties. Currently two algorithms to find and locate GRBs in data from ISGRI are in use, plus one program to detect GRBs 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.

![Diagram of IBAS software](image)

**Fig. 1.** Main components of the IBAS software.

The *Ibasalertd Program* is designed to combine the information it receives from the *Detector Programs*. The basic adopted logic is that triggers with high statistical significance are considered as valid GRBs even if they come from a single *Detector Program*, while triggers of lower significance require an independent confirmation from different data. 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...

If the event is genuine, the *Ibasalertd Program* determines the best available satellite attitude information to derive the GRB sky position, which is then delivered to the IBAS Clients by means of Alert Packets. In addition, if the GRB is located in the central $5^\circ \times 5^\circ$ of the IBIS field of view, which is covered by the OMC, the information is transmitted to the MOC, where an appropriate telecommand is automatically generated.
and sent to the satellite. This will reconfigure the observing mode of the OMC in order to place a CCD window on the position of the GRB.

**Distribution of the IBAS Alert Packets**

IBAS *Alert Packets* with the GRB information are sent via Internet, using the UDP transport protocol. We have developed a *Client Software* that allows the users to receive the *Alert Packets* and to easily use their content in the software commanding their telescopes. The IBAS *Client Software*, written in standard C language and tested on Sun Solaris, Linux and MacOSX, and its documentation can be downloaded from the ISDC web pages. The package contains one library and two simple programs (one to check the connection with the computer on which IBAS is running and one to print on the screen the content of the *Alert Packets*). Each packet is 400 bytes long, and consists of several fields, the format and content of which is explained in detail in the Client software documentation.

As described above, the IBAS GRB detection and alert distribution is mostly based on automatic processes. An interactive analysis, to confirm the event and to derive the most accurate GRB position, will generally be performed a few hours after the automatic delivery of the first alert message(s) with the preliminary coordinates. In designing an automatic GRB alert system, one is faced with the trade-off between the requirement to react in the shortest possible time and the desire to get the most accurate results (e.g. reality of the event, dimension of error region, etc...). Considering that the main users of the IBAS Alerts will be robotic telescopes with relatively large fields of view, specifically devoted to GRB afterglow searches, we have privileged the fast alert time requirement. This necessarily implies that some of the IBAS alerts might subsequently be found not related to real GRB events. Users not interested in the fastest reaction time can decide to receive only particular alert types. Five types of *Alert Packets* have been defined:

- **Packet type 1 : POINTDIR.**
  Many 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 will send a new POINTDIR packet each time a slew to a new pointing direction begins. The POINTDIR packet contains the pointing direction expected at the end of the slew and the expected time of slew end.

- **Packet type 2 : SPIACS.**
  Alert packets of type SPIACS will be sent after positive triggers detected with the SPI Anti Coincidence Shield. No position information will be available, unless the same GRB also triggers some of the imaging instruments (in such a case the position will come through other packet types). SPIACS packets contain the name of the file with the GRB light curve that is immediately available on the public ftp server of the ISDC. These light curves can be used in conjunction with those of other satellites to locate the GRB with the time delay triangulation method.

- **Packet type 3 : WAKEUP.**
  Packets of type WAKEUP are generated only once for each GRB and only if the GRB position information is available. They contain the preliminary position (R.A., Dec. J2000) derived for the GRB. These are the alerts with the shortest time delay (and consequently the highest chance of not being due to a real GRB event). Any (potential) GRB will generate only one WAKEUP packet. IBAS will then distribute more refined information as soon as it becomes available using packets of type 4.

- **Packet type 4 : REFINED.**
  These Packets provide refined information on a GRB event. IBAS will automatically generate a new REFINED packet only if the new information available has significantly smaller uncertainties and/or supersedes the one sent with previous packets. Zero to several REFINED packets can be generated for a given GRB.

- **Packet type 5 : OFFLINE.**
  These Packets are generated manually after an interactive analysis of the data performed off-line. The typical time delay can be from one to a few hours (or even longer in some cases). The OFFLINE alert packet represents the final confirmation (or rejection) of a GRB and contains the most accurate GRB properties distributed by IBAS.
FIRST RESULTS

The first two months after the launch of INTEGRAL have been devoted to the initial set up and activation of the instruments and to the Performance and Verification phase. During this period, the IBAS system has been operated each time suitable data were available (but with the automatic delivery of Alert Packets to external clients switched off). This allowed us to further test the system and to perform minor changes to the software in order to better adapt it to the in-flight performances of the instruments. At the time of writing (December 2002) INTEGRAL has already detected two GRBs in the field of view of IBIS: GRB021125 and GRB021219. The public distribution of the IBAS Alert Packets will begin in January 2003.

GRB021125 (Bazzano and Paizis 2002) occurred during an observation in which most of the available satellite telemetry was allocated to PICsIT for calibration purposes. Thus only a limited fraction of the events recorded with ISGRI could be transmitted to the ground. Unfortunately, due to the resulting gaps in the ISGRI data, the IBAS Detector Programs were in idle mode at the time of the burst and did not trigger in real time. The IBAS imaging programs were used in the off-line interactive analysis to locate the burst (see Figure 2). Further analysis resulted in a localization with an uncertainty of only 2 arcmin (Gros and Produit 2002), consistent with that independently derived with the IPN (Hurley et al. 2002a). After this event, we introduced some changes in the IBAS Detector Programs in order to be able to detect GRBs also during observations with limited ISGRI telemetry allocation (note, however, that such an instrument configuration is not supposed to occur often during routine operations).

The second GRB in the IBIS field of view, GRB021219 (Mereghetti et al. 2002), was found and correctly localized by the IBAS software in real time. The position derived by the IBAS software within ~10 seconds of the burst occurrence had an accuracy of ~20 arcmin, largely dominated by systematic uncertainties. In less than four hours these could be significantly reduced resulting in a 4 arcmin error box (Götz et al. 2002), which was subsequently confirmed with the IPN (Hurley et al. 2002b), as shown in Figure 3.

![GRB021125](image)

Fig. 2. Localization of GRB021125. The large circle (20' radius) is the first error region obtained with the IBAS programs, while the small one is the refined position (2' radius) obtained after a preliminary boresight correction (Gros and Produit 2002). The parallelogram is the IPN error box (Hurley et al. 2002a).
Fig. 3. Localization of GRB021219. The first IBAS error circle has a radius of 20′ (Mereghetti et al. 2002). The final localization obtained with an off-line analysis, shown by the small circle (4′ radius, Götz et al. 2002) is consistent with the IPN annulus (Hurley et al. 2002b).

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