In flight performance and first results of FREGATE

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Abstract. The gamma-ray detector of HETE-2, called FREGATE, has been designed to detect gamma-ray bursts in the energy range $[6-400]$ keV. Its main task is to alert the other instruments of the occurrence of a gamma-ray burst (GRB) and to provide the spectral coverage of the GRB prompt emission in hard X-rays and soft gammarays. FREGATE was switched on on October 16, 2000, one week after the successful launch of HETE-2, and has been continuously working since then. We describe here the main characteristics of the instrument, its in-flight performance and we briefly discuss the first GRB observations.

INTRODUCTION

The HETE-2 spacecraft (Ricker et al. 2002a, Doty et al. 2002) has been designed to distribute gamma-ray burst localizations within several seconds of the burst detection. The localization process and the distribution of rapid alerts is a complex chain of events which starts when a GRB is detected and identified as such. HETE-2 (hereafter HETE for simplicity) carries three experiments: the Soft X-ray Camera (SXC), The Wide-Field X-ray Monitor (WXM) and the FREnch GAmma Telescope (FREGATE). The latter is a traditional gamma-ray detector operating in the energy range $[6-400]$ keV, which was built by the Centre d’Etude Spatiale des Rayonnements (CESR) in Toulouse, France. FREGATE has three main goals:

- Detecting count rate increases and qualifying them as gamma-ray burst candidates.
- Performing GRB spectroscopy over a broad energy range (complementing and overlapping the WXM energy range).
- Monitoring the activity of galactic transients like the Soft Gamma Repeaters.

This paper describes FREGATE and explains how it is operated and calibrated in-flight. It also contains a brief discussion of the types of events detected during the first year of operation and a highlight of the preliminary scientific results of the mission.

| TABLE 1. FREGATE performances |
|--------------------------------|
| Energy range                  | 6 - 400 keV                |
| Effective area (4 detectors, on axis) | 160 cm$^2$               |
| Field of view (FWZM)          | 70$^\circ$                |
| Sensitivity (50 - 300 keV)    | $10^{-7}$ erg cm$^{-2}$    |
| Dead time                     | 10 $\mu$sec               |
| Time resolution               | 6.4 $\mu$sec              |
| Maximum acceptable photon flux| $10^3$ ph cm$^{-2}$ sec$^{-1}$ |
| Spectral resolution at 662 keV| $\sim$ 8$\%$              |
| Spectral resolution at 122 keV| $\sim$ 12$\%$             |
| Spectral resolution at 6 keV  | $\sim$ 42$\%$             |

DESCRIPTION OF THE INSTRUMENT

The FREGATE hardware consists of four identical detectors and one electronics box (see Figure 1). The instrument weights 14 kg and consumes 9 watts of electrical power. The four detectors are co-aligned on the spacecraft in order to share the same field of view. Contrary to the other HETE instruments (the WXM and the SXC), FREGATE has no localization capability, except the ability to recognize whether a transient occurred within or outside its field of view. The main characteristics of FREGATE are described in table 1.
Detectors

Each FREGATE detector consists of a cleaved NaI crystal (a cylinder 10mm thick and 71mm in diameter) read by a photomultiplier (Hamamatsu 1848, figure 2). In order to extend the spectral coverage of FREGATE at low energies, we chose cleaved crystals which have no dead layer. For the same reason the crystals are encapsulated in a beryllium housing which reduces the absorption of low energy gamma-rays. The thickness of the housing on the front side of the detectors is 0.22 mm and the overall transmission of the entrance window is larger than 65% at 6 keV and reaches 85% at 10 keV (see figure 3). At high energies the electronics limits the energy range to photons with energies below 400 keV. The geometric area of the sum of the four detectors for a source on-axis is nearly 160 cm². In addition there are two on-board radioactive sources of Barium 133 which illuminate the detectors from the outside with photons at 81 and 356 keV, allowing to monitor the gain of the detectors from the ground (see subsection "In-flight calibration" for more details).

Shield and Collimator

As shown in figure 2, the body of the detectors is surrounded by a graded shield made of lead, tantalum, tin, copper, and aluminium (0.8 mm of lead, 0.3 mm of tantalum, 0.7 mm of tin, 0.3 mm of copper, and 0.8 mm of aluminum). The aim of the shield is to prevent the photons from outside the field of view from reaching the crystal. The transparency of the shield is 5.5% at 150 keV, 55% at 300 keV, and 75% at 500 keV.

A peculiarity of the FREGATE detectors is that the shield goes beyond the front face of the crystal, reducing the field of view (FOV) of the instrument and acting as a collimator. The angular response of FREGATE with its collimator is shown in figure 4. While this collimator decreases the number of GRBs that FREGATE can detect, it plays an essential role for a mission like HETE where a synergy must be found between three sets of instruments.
with different properties and constraints. In the context of FREGATE the collimator provides the following advantages (in order of increasing importance):

- It increases the fraction of FREGATE GRBs which are within the FOV of the WXM.
- It decreases by a factor of two the count rate from the diffuse X-ray background.
- It restricts to 4 months per year the transit time of galactic sources within the field of view of FREGATE (instead of nearly 6 months).

While GRBs which are outside the field of view of the WXM cannot be localized, it was thought that the FOV of FREGATE should nevertheless be wider than the FOV of the WXM. The main reason for this choice was that a wider field of view of FREGATE ensured that all the GRBs detected by the WXM would illuminate at least 60 cm$^2$ of FREGATE detectors (as was the case for GRB010921, Ricker et al. 2002b). Moreover FREGATE-only GRBs are useful for broadband spectroscopic studies, they increase the statistics for rare events (like X-Ray Flashes or short GRBs) and they can be localized by the IPN.

Readout electronics

Each detector has its own analog and digital electronics. The analog electronics contain a discriminator circuit with four adjustable channels and a 14-bit PHA whose output is regrouped into 512 evenly-spaced energy channels (each approximately 0.8 keV wide). The (dead) time needed to encode the energy of each photon is 14 $\mu$s for the PHA and 9 $\mu$s for the discriminator. The digital electronics process the individual pulses, to produce the following output:

- Time histories in 4 energy channels (every 20ms).
- 128-channel energy spectra spanning the range 0-400 keV (every 80 ms).
- A circular buffer containing the most recent 65536 photons tagged in time (resolution 6.4 $\mu$s) and in energy (resolution 0.8 keV).

On-board software

The main tasks of the on-board software include the configuration of the instrument, the acquisition of data from the electronics, their packaging for the telemetry, and the search for excesses in the count rate.

Configuration of the instrument. The output of FREGATE depends on a number of adjustable parameters such as the settings of the high voltages, the limits of the energy channels, the trigger criteria, or the on-board data compression. These parameters are described in a configuration file which can be uploaded when the spacecraft is in contact with one of the three primary ground stations (PGS, see Crew et al. 2002). When a new configuration file is uploaded, the on-board software modifies the configuration of FREGATE accordingly.

Data packaging. Every 20 ms the FREGATE Digital Signal Processor (DSP) reads the data from the electronics and prepares the data for the telemetry. The data products generated by FREGATE are described in the next Section.

Search for excesses. The on-board software also scans the data in real time to search for sudden increases in the count rate recorded by the instrument. This work is described in details in Section "FREGATE triggers" below.

DATA TYPES

FREGATE generates 4 types of data: Housekeeping (HK), light curves and spectra generated by the FREGATE DSP, light curves generated by one of the on-board tranputers (the so-called X-$\gamma$ tranputer), and burst data. Housekeeping data are produced continuously; light curves and spectra are produced when the high voltages are on; and burst data are produced only after a trigger.

The HK data and the light curves produced by the on-board tranputer will not be discussed here, however, the continuous data and the burst data generated by the FREGATE DSP are explained in detail below.
FIGURE 5. Continuous data generated by FREGATE during nighttime. From top to bottom, the light curves in the 4 energy bands B, A, C, and D (see text) for the sum of the 4 detectors. The data have been regrouped in 4 second bins for clarity, the actual resolution of the data is 0.16 seconds. The large peak in energy band D is due to protons trapped in the SAA.

Light curves and spectra generated by the DSP

During nighttime, when the high voltages are on, FREGATE produces continuous light curves and spectra. The light curves represent the count rates measured by the 4 detectors in 4 broad energy channels with time resolutions of 0.16 and 0.32 s. The limits of the energy channels are usually set to

- 6 - 40 keV for channel A.
- 6 - 80 keV for channel B.
- 32 - 400 keV for channel C.
- > 400 keV for channel D.

An example of these data is shown in figure 5.

Simultaneously FREGATE generates four 128-channel energy spectra covering the energy range 0-400 keV every 5 or 10 seconds (but the electronics threshold and the absorption of the beryllium window reduce the effective energy range to 6-400 keV).

Burst data

When a trigger occurs, burst data are generated in addition to the continuous data. The burst data consist of 256k photons (64k per detector) tagged in time (with a resolution of 6.4 µs) and in energy (256 energy channels spanning the range 0-400 keV). These burst data allow detailed studies of the spectro-temporal evolution of bright GRBs. An example of the gain provided by the burst data is shown in figure 6.

FREGATE OPERATION

FREGATE operations are driven by alternating nighttime and daytime periods. Because HETE instruments always point in the antisolar direction they have the earth in their field of view during about 45 min per orbit (the duration of one orbit is 90 min); this is the daytime period.

During daytime the High Voltages of the detectors are switched off, partly to reduce the amount of data produced by the spacecraft and partly to avoid the triggers due to solar X-ray flares reflected on the atmosphere of the Earth (see figure 11).

During nighttime the high voltages are switched on. The detectors continuously record the gamma-ray flux in four energy bands and these data are processed by the DSP to search for excesses due to GRBs (see next section).

In-flight calibration

Since FREGATE records only the time and the energy of the photons, we need to calibrate only the FREGATE timing and energy scales.

The FREGATE time is directly derived from the HETE time and the calibration of FREGATE time is, in reality, the issue of the spacecraft time calibration which is not discussed here.

As mentioned above, the energy calibration of the detectors is made possible by two on-board radioactive sources of Barium 133 which illuminate the detectors from the outside (133Ba emits gamma-ray lines at 81 and 356 keV, with a half-life of 10.5 years). A typical background spectrum, accumulated for 1200 seconds, is shown in figure 7. These radioactive sources allow the monitoring of the gain of the four detectors of FREGATE with a time resolution of a few minutes (the gain is manifested in the response of the detectors to photons with a given energy). The gain fluctuates on two timescales: along one orbit (90 min) and on a longer period of several weeks.

On the short term, the gain changes with the orientation of the magnetic field along the orbit. This effect is due to the incomplete collection of the photoelectrons on the first anode of the PMT (which has no magnetic shield). A typical example of such variations is shown in figure 8.

The gain also exhibits a tendency to decrease on the long term. this trend is monitored on the ground and compensated by regular increases of the high voltages (by a few percent) every 2 months.
Energy response

The in-flight energy response of a gamma-ray detector is the combination of its physical response, its intrinsic non-linearities, and the gain variations. The physical response of FREGATE detectors has been evaluated with detailed Monte Carlo simulations. The output of the simulation program has been checked against ground calibrations made with 9 radioactive sources having energies in the range 8 keV ($^{65}$Zn) to 1332 keV ($^{60}$Co). The same sources provide a measure of the intrinsic non-linearities of the detectors. Finally the gain fluctuations are measured on-board as explained above.

The quality of the spectral response of FREGATE has been evaluated via the deconvolution of the hard X-ray emission from the Crab nebula. The spectrum of the Crab nebula has been constructed from the amplitude of the Crab occultation steps observed at various energies, see figure 9. The deconvolved spectrum is fully compatible with the well known spectrum of the Crab nebula for energies between 10 keV and 200 keV and for angles between 0° and 50°. This procedure and the results obtained are described in details by Olive et al. (2002a).

Ground operations

The operational tasks on the ground are very simple. In normal operation they include the following actions:

- Upload the HV ON/OFF sequences.
- Check the health of the detectors.
- Adjust the gains and update the configuration.
- Search for events which didn’t fire the on-board trigger.

When an astronomical event is detected it is also necessary to update the FREGATE catalog(s) and to construct the response matrices if it is within the field of view.
FIGURE 9. Crab occultation: the two steps in the light curve are due to the transit of the Earth in front of the Crab nebula. The light curve, which has a temporal resolution of 5s, shows the total count rate measured by the four FREGATE detectors in the energy range 6-80 keV. The Crab is approximately 30° off-axis.

FREGATE TRIGGERS

GRB detection

The data recorded by FREGATE are searched for GRBs and other astronomical transients both on-board and on the ground. Two real-time programs run on-board: the DSP trigger and the transputer trigger. The former is described below. The transputer trigger has been designed to add more flexibility and to search for excesses in the combined data from FREGATE and the WXM, it is described by Tavenner et al. 2002.

The on-board GRB detection is completed by two programs which automatically process the data when they arrive at the ground. These programs are more efficient than the on-board processing for the detection of long or soft events, they are described in Butler et al. 2002 and in Graziani et al. 2002.

DSP trigger. The DSP triggers when the count rate measured over a time interval $\Delta t$ exceeds the average count rate, measured over the last $T$ seconds, by more than $k$ standard deviations. Four timescales ($\Delta t$) are used for the trigger detection: 20 ms, 160 ms, 1.3 s, and 5.2 s. The duration of the background integration is an adjustable parameter, usually set to 30 s. The trigger thresholds $k$ are adjustable and currently set to values between 4.5 and 6. The trigger detection algorithm works in parallel in the energy channels B (6-80 keV) and C (30-400 keV). In order to decrease the rate of false triggers, due to electronic noise or particles, we discard the triggers which are detected by only one of the four detectors. When the DSP triggers it sends an alert message to the HETE trigger monitor (Crew et al. 2002, VanderSpek et al. 2002), which alerts the other instruments of HETE and the VHF transmitter. Simultaneously FREGATE will go into burst mode when it receives a message from the on-board trigger monitor (e.g. following a WXM trigger). Because the high-energy sky is essentially variable, many types of events can trigger FREGATE. We summarize below the origin of the triggers detected during the first year of the mission.

Non-astrophysical events

Pre-SAA electrons. In addition to the high fluxes of protons detected in the South Atlantic Anomaly (SAA), energetic electrons are sometimes trapped in electron radiation belts crossed by HETE a few minutes before the SAA. These populations of energetic electrons are highly variable and they reach a maximum in the days following large coronal mass ejections (CMEs) from the Sun. When HETE goes through these radiation belts (at longitudes between 80 and 100 degrees) FREGATE measures high count rates due the interaction of the electrons with the spacecraft (producing X-rays) and with the detectors (see figure 10). These high count rates will sometimes trigger FREGATE.

Solar flares reflected on the Earth's atmosphere. FREGATE high voltages are usually switched off during daytime. However, there are occasions when we want FREGATE on with the Earth in the field of view. In this case the low energy threshold of FREGATE make it very...
sensitive to solar flares reflected by the atmosphere of the Earth. An example of such a flare (class M2.2) is shown in figure 11.

**Noise triggers.** The noise triggers are due to the statistical fluctuations of the background count-rate measured by the detectors. FREGATE triggers only when it detects two simultaneous excesses in the sum of detectors 1+2 AND in the sum of detectors 3+4, this strategy reduces the number of noise triggers to less than 1 per month.

**GRBs and other astrophysical transients**

**SCO X-1.** SCO X-1 is the brightest hard X-ray source in the sky. It exhibits rapid flaring (see figure 12) and generates many triggers when the trigger is enabled in energy channel B (6-80 keV). From the beginning of April to the end of July, when SCO X-1 is within the field of view of FREGATE, the trigger is disabled in channel B, completely suppressing SCO triggers.

**X-ray bursts.** X-ray bursts (XRBs) are due to thermonuclear explosions at the surface of accreting neutron stars in binary systems. Several dozen X-ray bursters are present in the galactic bulge. When FREGATE has the galactic bulge within its field of view it detects a few XRBs per day. These events do not trigger FREGATE, whose low energy trigger is disabled during summer time (when SCO X-1 is in the field of view, see above), but they are identified a posteriori by the ground processing. A sure way to identify XRBs is to associate their arrival direction with a known X-ray source. The WXM is well suited to do this job, but its field of view is only half the field of view of FREGATE, implying that the identification of the XRBs detected by FREGATE at large off-axis angles must rely solely on their spectro-temporal properties. An example of an XRB detected by FREGATE can be found in figure 13. A list of X-Ray Bursts detected and localized by the WXM during the summer 2001 is given in Sakamoto et al. 2002.

**Soft Gamma-ray Repeaters.** During the summer 2001, both SGR1900+14 and SGR1806-20 were active. From the beginning of June to the end of August FREGATE detected about 30 short bursts which can be attributed to these Soft Gamma Repeaters (figures 6 and 13). Six of these bursts were localized by the
Gamma-Ray Bursts. Gamma-ray bursts constitute the main scientific target of HETE. Between October 2000 and September 2001, FREGATE has detected 32 confirmed GRBs and a few unconfirmed events (see Dezalay et al. 2002 for a list). We estimated the sensitivity of FREGATE to be $10^{-7} \text{ erg cm}^{-2}$ in the energy range [50-300] keV (Dezalay et al., 2002). Figure 15 shows the number of confirmed GRBs detected by FREGATE since it was turned on in October 2000. The higher number of GRBs per month after May 2001 is due to an increased observational efficiency, which should result in the detection of a larger number of GRBs in 2002. Some interesting results have already been obtained with the GRBs detected during the first year of FREGATE operation, the reader will find some of them in these proceedings and a short list is given in the Conclusion below.

CONCLUSION

The first year of FREGATE operation shows that it fulfills the goals for which it has been designed: alerting HETE when a GRB occurs, performing the broadband spectroscopy of GRBs and other astrophysical transients (SGRs and XRBs), and providing a census of galactic and extragalactic high energy transients. Regarding this last issue, we note that, as a consequence of the anti-solar pointing strategy of HETE, FREGATE observes the same portion of the sky during more than $3 \times 10^6$ seconds per year. In addition FREGATE has been successfully integrated into the Interplanetary Network of gamma-ray burst detectors (Hurley et al. 2002).

This volume contains some significant scientific results obtained by HETE and FREGATE. The followup of GRB010921 detected by FREGATE and localized with the WXM has led to the identification of the first HETE afterglow at a redshift $z=0.45$ (Ricker et al. 2002b, Price et al., 2002). The spectro-temporal evolution of a bright burst from SGR1900+14 in analysed in detail by Olive et al. (2002b). Barraud et al. (2002) discuss the existence of very soft GRBs (probably similar to the X-Ray Flashes discussed by Heise, 2002) which have less than 10% of their fluence above 30 keV.

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