Burst Detector Sensitivity: Past, Present & Future

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Abstract. I compare the burst detection sensitivity of CGRO’s BATSE, Swift’s BAT, the GLAST Burst Monitor (GBM) and EXIST as a function of a burst’s spectrum and duration. A detector’s overall burst sensitivity depends on its energy sensitivity and set of accumulations times $\Delta t$; these two factors shape the detected burst population. For example, relative to BATSE, the BAT’s softer energy band decreases the detection rate of short, hard bursts, while the BAT’s longer accumulation times increase the detection rate of long, soft bursts. Consequently, Swift is detecting long, low fluence bursts ($2-3 \times$ fainter than BATSE).

What is the relative sensitivity of different detectors for detecting gamma-ray bursts, and how should this sensitivity be compared? How do these differences shape the observed burst populations, which must be taken into account in determining the underlying burst distribution? Here I compare BATSE’s Large Area Detectors on CGRO (the past), the Burst Alert Telescope (BAT)[1] on Swift (the present), and the GLAST Burst Monitor (GBM) and EXIST (the future). BATSE and the GBM are/were sets of NaI(Tl) detectors while the BAT and EXIST are/will be CZT coded mask detectors. The energy range of NaI(Tl) detectors is $\sim 20–1000$ keV while for CZT it is $\sim 10–150$ keV. I apply a semi-analytic methodology using simplified models of the trigger systems of the different detectors.

Most instruments detect bursts using either rate triggers or image triggers. A rate trigger determines whether the increase in the number of counts in a time bin $\Delta t$ and energy band $\Delta E$ over the expected number of background counts is statistically significant. An image trigger determines whether the image formed from the counts in the time bin $\Delta t$ and energy band $\Delta E$ contains a new point source. Usually an image trigger is preceded by a rate trigger that starts the imaging process[2]; the rate trigger is set to permit many false positives that are eliminated by the image trigger. If the number of burst counts is $S$ and the number of non-burst counts is $B$, then the rate trigger significance $\sigma_r$ (for BATSE and the GBM) and the image trigger significance $\sigma_i$ for $\Delta t$ and $\Delta E$ are

$$\sigma_r = \frac{S}{\sqrt{B}} \quad \text{and} \quad \sigma_i = \frac{f_c S}{\sqrt{B + S}}$$

(1)

where $f_c$ accounts for the finite size of the detector pixels. For Swift $f_c \sim 0.7[3]$, which explains why for a given burst the rate trigger significance is greater than the imaging significance[4]. The BAT uses a more complex rate trigger than shown above. For directions other than the burst position the counts $S$ from the burst contribute to the
average flux level, and therefore in imaging $S$ is compared to $\sqrt{B+S}$. A trigger occurs when $\sigma_r$ or $\sigma_i$ exceeds a threshold value that is sufficiently high for a small probability of false positives. Because of the similarity of $\sigma_r$ and $\sigma_i$, particularly since usually $B \gg S$ near threshold, the methodologies for evaluating the sensitivity of rate and image triggers are essentially the same[5].

Whether a given detector and its trigger system detects a burst depends on the number of counts $S$ the burst produces in time bin $\Delta t$ and energy band $\Delta E$. If bursts differed only in their intensity, we could use a common measure of burst intensity, but bursts differ in their temporal and spectral properties, and thus a given detector is more sensitive to some burst types and less to others. While it is impossible to characterize a burst completely by only a few parameters, approximate burst types can be described by a few parameters. For burst detection, I characterize bursts by: $E_p$—the energy at the peak of $E^2N(E) \propto \nu f\nu$ for the spectrum averaged over $\Delta t$; and $T_{90}$—the time duration for 90% of the flux. I characterize the burst intensity by the peak flux $F_T$ over 1 s in the 1–1000 keV band. A detector does not measure $F_T$ directly; since a spectral fit is necessary to convert from counts to flux, $F_T$ need not be over $\Delta E[5]$.

I first evaluate the sensitivity of the four detectors to $E_p$, disregarding the burst duration. Thus I assume that bursts have constant emission over $\Delta t=1$ s. Then $S$ is proportional to the burst spectrum times the detector efficiency integrated over $\Delta E$. BATSE used only one value of $\Delta E$ at any given time, typically $\Delta E=50$–300 keV, but later detectors use a set of $\Delta E$ simultaneously. Figure 1 shows the threshold $F_T$ as a function of $E_p$ for BATSE, BAT, GBM and $EXIST$. While I characterize the spectrum primarily by $E_p$, there remains a dependence on the high and low energy spectral indices, $\beta$ and $\alpha$ (not shown by Figure 1). In all cases I use the maximum sensitivity over the FOV. The scalloping results from multiple values of $\Delta E$.

As a CZT detector, the BAT’s sensitivity is shifted to lower energy than BATSE’s. The GBM’s detectors will be smaller than BATSE’s, while $EXIST$ will have larger detectors
FIGURE 2. The ratio of the detector sensitivity for a trigger system using a set of $\Delta t$ values to the rate trigger sensitivity for $\Delta t = 1.024$ s alone; ratios less than 1 indicate an increase in sensitivity resulting from additional values of $\Delta t$. The dashed curve is for BATSE’s set of $\Delta t$, while the dashed curve is for the BAT.

than the BAT. Note that these sensitivity curves are all for $\Delta t = 1$ s; increasing $\Delta t$ increases the BAT’s sensitivity to long bursts.

As $\Delta t$ increases, the number of burst counts $S$ may increase but the number of background counts $B$ definitely increases. Thus there is a competition between changes in $S$ and $B$ as $\Delta t$ changes. The effect on the sensitivity of increasing or decreasing $\Delta t$ depends on the burst lightcurve; the duration $T_{90}$ is a key parameter characterizing the lightcurve. If $T_{90} \ll \Delta t$ then the dilution of the burst counts by the background can be decreased by decreasing $\Delta t$, but if $T_{90} \gg \Delta t$ then increasing $\Delta t$ might increase the number of burst counts relative to the background. Detectors use more than one $\Delta t$; the overall sensitivity is the lowest value of $F_T$ for any $\Delta t$. Figure 2 shows as a function of $T_{90}$ the ratio of the detector sensitivity for a set of $\Delta t$ to the rate trigger sensitivity for $\Delta t = 1.024$ s alone; ratios less than 1 indicate an increase in sensitivity resulting from the additional values of $\Delta t$ and the trigger type. The burst is assumed to have an exponential lightcurve. BATSE (dashed curve) used a simple rate trigger with $\Delta t = 0.064$, 0.256 and 1.024 s. Thus, for $T_{90} > 1.024$ s the $\Delta t = 1.024$ s trigger dominates, and the ratio equals 1, while for $T_{90} < 1.024$ s the smaller $\Delta t$ values increase the sensitivity (smaller ratios) to short duration bursts. The BAT, GBM and EXIST (will) use both smaller and longer $\Delta t$ values than BATSE did. The solid curve on Figure 2 was calculated for the BAT’s image trigger; note the increase in sensitivity over BATSE’s set of $\Delta t$ for both long and short bursts. The increase in sensitivity to short duration bursts is not as dramatic as for long duration bursts because $\sigma_i$ does not decrease indefinitely as $B$ decreases for fixed $S$ (see eq. 1). The reduced sensitivity of an image trigger relative to a simple rate trigger for very short bursts does NOT mean that a rate trigger is superior to an image trigger: an image trigger localizes the burst, and does not require a model of the background rate.

The spectral and temporal dependencies of the burst sensitivity can be combined to produce the threshold $F_T$ as a function of both $E_p$ and $T_{90}$. Figure 3 presents the ratio of the sensitivities of the BAT and BATSE; a ratio less than one indicates that the BAT
is more sensitive than BATSE at that particular set of $E_p$ and $T_{90}$. Also plotted are the $E_p$ and $T_{90}$ for a set of BATSE bursts. As can be seen, the short, hard bursts are in a region of parameter space where the BAT is less sensitive than BATSE while the BAT is more sensitive to long, soft bursts. The contours’ gradient shows that the BAT detects fewer short, hard burst because its energy band is lower than BATSE’s was, and the BAT detects more long, soft bursts both because of its lower energy band and its greater sensitivity to long bursts. This explains the shift in the duration distributions. Because the BAT is significantly more sensitive to long bursts, the average fluence detected by the BAT is $\sim 2.5$ times fainter than BATSE’s. As a burst’s redshift is increased, its duration is dilated and its spectrum is redshifted. Thus high redshift bursts are shifted towards the parameter space region where *Swift* is particularly sensitive. Note that *Beppo-SAX* and *HETE-II* use(d) imaging triggers with low energy detectors, explaining why these two detectors detect(ed) few short bursts and many X-ray rich bursts and X-ray Flashes.

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