Burst Populations and Detector Sensitivity

David L. Band

Code 661, NASA/Goddard Space Flight Center, Greenbelt, MD 20771

Abstract. The $F_T$ (peak bolometric photon flux) vs. $E_p$ (peak energy) plane is a powerful tool to compare the burst populations detected by different detectors. Detector sensitivity curves in this plane demonstrate which burst populations the detectors will detect. For example, future CZT-based detectors will show the largest increase in sensitivity for soft bursts, and will be particularly well-suited to study X-ray rich bursts and X-ray Flashes. Identical bursts at different redshifts describe a track in the $F_T$-$E_p$ plane.

INTRODUCTION

Burst detectors are sensitive in different energy bands, and some bursts emit most of their energy at 10 keV while others emit at 1 MeV. Here I present a methodology to compare the burst populations that different detectors will detect. The issue is what bursts will cause a detector to trigger.

The standard rate trigger monitors a detector’s count rate for a statistically significant increase[1]. The counts are binned over an energy range $\Delta E$ and time bin $\Delta t$, and the number of counts in this bin is compared to the expected number of background counts. For example, BATSE used $\Delta E=50–300$ keV for most of the CGRO mission and $\Delta t =0.064, 0.256$ and $1.024$ s. Usually the expected background is calculated from the counts accumulated over a period (e.g., 20 s long) before the bin being tested, and periodically (e.g., every 10 s) the background is recalculated. Most often the background is modelled as a constant in time, but polynomials can be fit.

A rate trigger tests the null hypothesis that only background counts are present. The test is whether the probability that the observed number of counts in a $\Delta E$-$\Delta t$ bin is a fluctuation is smaller than a threshold value. In the Gaussian limit the fluctuations are measured in units of $\sigma$, the square root of the expected number of counts, and the threshold fluctuation probability can be mapped into the number of $\sigma$. Thus the test is whether the observed number of counts exceeds the expected number by more than a threshold multiple of $\sigma$.

When more than one detector is present (e.g., BATSE’s 8 detectors, the 12 NaI detectors of GLAST’s GBM) the requirement may be that more than one detector trigger. Almost always a detector’s sensitivity varies across the field-of-view (FOV). If two detectors must trigger, the spatial sensitivity depends on the angle to each detector.

For coded mask detectors such as HETE II’s WXM and Swift’s BAT the rate trigger is followed by imaging, and a new point source in the image must confirm the burst trigger.
A COMMON SENSITIVITY VOCABULARY

A detector’s sensitivity is the minimum count rate that triggers the detector. This corresponds to the burst’s peak count rate when integrated over $\Delta E$ and $\Delta t$. Because bursts are not constant for seconds and burst lightcurves differ at different energies, the sensitivity will differ for different sets of $\Delta E$ and $\Delta t$, and a smaller threshold count rate for one set of $\Delta E$ and $\Delta t$ compared to another set may not indicate that fainter bursts will be detected. In addition, because of the detector’s finite energy resolution, the count rate over $\Delta E$ is not the photon flux integrated over $\Delta E$, and the count rates for two detectors in the same nominal $\Delta E$ cannot be compared directly. This complicates the comparison between different detectors and different triggers for the same detector. A common sensitivity measure is necessary; this quantity will be burst-dependent.

The sensitivity measure should be a measure of the burst’s intensity that is independent of the detector or the trigger specifics[2]. I propose $F_T$, the photon flux integrated over 1–1000 keV and 1 s. This may not be the most physically interesting or relevant intensity measure, but it is closely related to the count rate that triggers the detector. Converting the count rate over $\Delta E$ to $F_T$ requires the spectrum at the time of the peak flux, but this spectrum is required for the conversion from peak count rate to peak photon flux (e.g., BATSE’s 50–300 keV peak flux). For a given detector trigger (i.e., with a choice of $\Delta E$ and $\Delta t$) $F_T$ will depend on the particulars of the burst: the lightcurve around the time of the peak flux, and the spectrum at this time. Here I do not focus on the dependence on the lightcurve (i.e., on $\Delta t$), but instead on the spectrum.

Burst spectra can be described as $N_E \propto E^\alpha \exp[-E/E_0]$ at low energy and $N_E \propto E^\beta$ at high energy. The peak of $E^2N_E \propto v f_V$ occurs at $E_p = (2 + \alpha)E_0$, and thus $E_p$ is a measure of spectral hardness. $F_T$ is most strongly a function of $E_p$, although there is a residual dependence on $\alpha$ and $\beta$.

Therefore, detectors should be compared through sensitivity curves in the $F_T$-$E_p$ plane. Bursts populate this plane: XRFs have small values of both $F_T$ and $E_p$, while the burst hardness-intensity correlation means that bursts will populate a band from the lower left to the upper right of the $F_T$-$E_p$ plane.

CALCULATION METHODOLOGY

While the sensitivity can be calculated in detail for each detector as a function of the source position in the FOV, taking into account variations in the background, here I describe simplified calculations[2].

**Detector response**—I assume that the detectors are “diagonal,” the measured count energy is equal to the actual photon energy (i.e., infinite energy resolution). Since I integrate spectra and background over broad energy bands, this is a reasonable assumption, although at high energy a significant fraction of the photons are downscattered. In general I parameterize the energy dependence of the effective area as a series of power laws.

**Background**—In general I model the background as the sum of the aperture flux plus a constant (cts s$^{-1}$ keV$^{-1}$); in some cases I use the background rates for a given detector quoted in the literature. The aperture flux is the product of the cosmic background flux...
and $\Omega$, the average solid angle of the sky visible on the detector plane. $\Omega$ is calculated from formulae for rectangular and circular detectors.

Energy bands—I use the sets of $\Delta E$ applicable for each detector. For proposed detectors I use a set that optimizes the sensitivity.

Additional factors—I also consider the fraction of a coded mask that is open, the fraction of the detector plane that is active, and the angle to the second most sensitive detector when two detectors must trigger.

Factors not considered—I do not consider the high energy transparency of the detectors’ side shields or coded masks (except when the mask transparency is included in the effective area). I also do not include scattering off the Earth or the spacecraft. The background calculation is crude, particularly at high energy.

APPLICATIONS

This methodology was originally developed to compare different detectors. Fig. 1 compares the sensitivity of BATSE, a set of NaI detectors, to Swift, a CZT detector. CZT is sensitive in the 10–150 keV band as opposed to NaI’s 30–1000 keV sensitivity. Therefore, Swift’s increase in sensitivity over BATSE will be greatest at low energy.

The scalloping in the Swift sensitivity curve results from triggering on more than one $\Delta E$. The optimal set of $\Delta E$ can be found by comparing the sensitivities of different $\Delta E$, as is shown by Fig. 2 from a trade study for GLAST’s GBM NaI detectors[3]. In this case the second set of $\Delta E$ is as effective as the first, but does not include the $\Delta E=50–300$ keV that was BATSE’s primary trigger band.

Fig. 3 shows the position in the $F_T$-$E_p$ plane that bursts at $z=1$ with $F_T=7.5$ ph cm$^{-2}$ s$^{-1}$ and $E_p=30$, 100, 300 and 1000 keV would have if they originated at higher $z$. The calculation accounts for the narrowing of pulses at higher energy. The ‘+’ are at half-integral $z$ values up to $z=10$. Also shown are the sensitivities for BATSE, Swift and EXIST for bursts with $\alpha = -1$ and $\beta = -2$. 
FIGURE 2. Sensitivity for the GBM NaI array on GLAST for $\Delta t = 1$ s and two sets of $\Delta E$; $\alpha = -1$ and $\beta = -2$ are assumed. For the first set (solid curves, left to right) $\Delta E = 5$–100, 50–300, and 100–1000 keV while for the second set (dashed curves, left to right) $\Delta E = 5$–1000 and 50–1000 keV.

FIGURE 3. Tracks in the $F_T$–$E_p$ plane for identical bursts at different $z$. Also shown are the sensitivities for BATSE, Swift and EXIST for bursts with $\alpha = -1$ and $\beta = -2$. The bursts would have $F_T = 7.5 \text{ ph cm}^{-2} \text{ s}^{-1}$ at $z = 1$.

REFERENCES

1. Band, D. 2002, ApJ, 578, 806
2. Band, D. 2003, ApJ, 588, 945
3. Band, D., et al. 2004, “GLAST’s GBM Burst Trigger” in these proceedings