

The Trigger Algorithm for the Burst Alert Telescope on Swift

E. E. Fenimore*, David Palmer*, Mark Galassi*, Tanya Tavenner*, Scott Barthelmy†, Neil Gehrels†, Ann Parsons† and Jack Tueller†

*Los Alamos National Laboratory, Los Alamos, NM USA

†Goddard Space Flight Center, Greenbelt, MD USA

Abstract. The Swift Burst Alert Telescope (BAT) is a huge (5200 cm²) coded aperture imager that will detect gamma-ray bursts in real time and provide a location that the Swift satellite uses to slew the optical and x-ray telescopes. This huge size is a challenge for the on-board triggering: trends as small as 1% over a second is equivalent to a 1 σ statistical variation in 1 second. There will be 3 types of triggers, 2 based on rates and one based on images. The first type of trigger is for short time scales (4 msec to 64 msec). These will be traditional triggers (single background) and we check about 25,000 combinations of time-energy-focal plane subregions per second. The second type of trigger will be similar to HETE: fits to multiple background regions to remove trends for time scales between 64 msec and 64 seconds. About 500 combinations will be checked per second. For these rate triggers, false triggers and variable non-GRB sources will be rejected by requiring a new source to be present in an image. The third type of trigger works on longer time scales (minutes), and will be based on routine images that are made of the field of view.

INTRODUCTION

The Burst Alert Telescope (BAT) on Swift is a large (5200 cm²) CZT-based coded aperture imager. BAT's primary role on the Swift satellite is to detect when a gamma-ray burst (GRB) starts, quickly locate it, and direct the Swift satellite to point the optical and x-ray telescopes at the source. The BAT trigger must not only detect the occurrence of a GRB, but it also must select the time periods to form an image. This requires the triggering code to identify a range of times (the "background" period) when there is no apparent emission from the GRB and a range of times (the "foreground" period) where the GRB probably will produce the strongest image.

The BAT triggering code has three types of triggers. Two of these are "rate" triggers based on statistically significant increases in the counting rate in the focal plane (or a portion of the focal plane), and one is an "image" trigger based on new significant sources found in images of the field of view (FOV). The rate triggers are divided into the "short" rate triggers (with foreground periods of less than or equal to 64 msec) and "long" rate triggers (with foreground periods larger than or equal to 64 msec). The image triggers are intended for longer periods of time (from 64 sec to many minutes).

One goal is to explore the widest possible parameter space. As such, as many triggers as possible will be

run simultaneously until the flight computer is nearly saturated. Thus, special attention will be paid to the CPU usage.

It is not hard to design a triggering code that responds to GRBs. The real challenge in the triggering code is to avoid false triggers. This is a special problem with BAT because its huge size means that a very slight trend can appear to be a significant increase in the count rate: a 1% change in the count rate over 1 sec appears to be a 1 σ variation. Thus, the chief danger is false triggers due to trends in the background, uninteresting variations of sources in the FOV, or minor configuration changes (such as automatic gain adjust) that produces the appearance of a statistically significant increase. Our chief defense against such false triggers is that we will form an image and the trigger will only proceed to slewing the satellite if there is a clear point source (thus eliminating events associated with particle variations) that is not in the direction of known variable sources.

SHORT RATE TRIGGERS

Running many short time scales through a triggering code can require most of the CPU time. Fortunately, the background counting rate of BAT is not expected to change on short time scales (i.e., less than a few seconds). Thus, for the short time scales we will use simple

traditional triggers where there is a single background period of fixed duration before the foreground period. This is the type of trigger that was used on all GRB experiments from Vela to BATSE.

The short trigger looks for statistically significant increases in the count rate on five time scales: 4, 8, 16, 32, and 64 msec. This is done for nine different regions of the focal plane (four quadrants, the left half, right half, top half, bottom half, and the full focal plane) and for four energy ranges. Thus, there are 36 combinations of focal plane regions and energy ranges. Within each second there are 250 4-msec samples to check, 250 8-msec samples to check (assuming the foreground periods are checked at all 4-msec phases), 125 16-msec samples (assuming the foreground periods are checked at all 8-msec phases), 62 32-msec samples, and 32 64-msec samples.

Overall, there are more than 25,000 short trigger samples to check every second. The calculational effort is optimized by having the code responsible for reading the photons from the focal plane search for the maximum number of counts at each time scale and region-energy combination. Every 256 msec, the short triggering code is sent 180 samples: the maximum counts seen in the 5 time scales and the 36 region-energy combinations. The triggering code only has to check the maximum sample that occurred within each time scale-region-energy combination, not every observed sample. By having the code that ingests the photons identify the maxima, we can effectively check 25,000 samples a second with just 720 actual trigger calculations.

All of the short trigger calculations for a particular set of 180 samples uses the same background rates based on a 1.024 sec period. These background rates are determined by the long trigger algorithm. Let $C_{i,k}$ be the maximum counts observed on the 2^k msec time scale in the i^{th} region-energy combination. Let B_i be the counts observed in 1024 msec for the i^{th} region-energy combination. The short trigger "score" is effectively the σ^2 of the net signal relative to the expected statistical variation. (We use σ^2 to avoid taking square roots: one can more easily find the maximum of σ^2 than the maximum of σ and both methods will point to the same sample.) The precise definition of the short trigger score is:

$$S = \frac{(C_{i,k} - B_i 2^{k-10})^2}{C_{i,k} + \sigma_{\min}^2}. \quad (1)$$

Here, σ_{\min}^2 is a commandable control variable to ensure that there is a minimum variance when the counts are small. A trigger is declared if S is greater than a threshold, $\sigma_{\text{threshold}}^2$. Each of the triggers for the 180 combinations are controlled by three commandable variables: an enable/disable, $\sigma_{\text{threshold}}^2$, and σ_{\min}^2 .

LONG RATE TRIGGERS

To avoid trends on longer time scales, one must fit a function to the background and remove the trend. This is the technique pioneered by the HETE GRB trigger [2, 3]. The long rate triggers are much more complicated than the short rate triggers and are based on time series with 64 msec time resolution. To cover as wide a parameter space as possible, the triggering code must be very efficient. In previous trigger algorithms (such as HETE), most of the CPU usage is for forming sums of counts. For each long trigger, one needs to have the sum of counts in several background periods (probably involving a few hundred 64 msec samples) plus the counts in foregrounds ranging from 64 msec in duration up to perhaps 64 sec. The trick to an efficient triggering algorithm is to store the integral sum of counts, not the counts within samples. The BAT triggering code maintains 36 time series in circular buffers (for the 9 detector regions and 4 energy ranges). Each time series consists of the integer sum of the counts from when the instrument was turned on up to time T :

$$I_i(T) = \sum_0^T C_i. \quad (2)$$

To obtain the sum of counts within a particular time period (say T_1 to T_2), one needs only a single arithmetic step, $I_i(T_2) - I_i(T_1)$, rather than a sum over the samples between T_1 and T_2 . (Eventually, the integer sum will overflow the register capability of the computer. If the difference is negative, one just adds the maximum range of the computer registers.)

A second integral sum adds up the number of invalid samples for each of the 36 region-energy combinations. For example, if there is a configuration change in one of the quadrants, a 1 is added to the corresponding invalid integral sum. Whenever we seek the number of counts from a period of time that includes that sample, we also check that the difference of the integral sum of invalids that cover that same duration is zero. For every time that the high voltage is off or something else disables the detectors, a 1 is added to the sum of invalid samples. The trigger code runs all the time and each criterion turns on as soon as the corresponding difference in the sum of invalid samples is zero. Thus, criteria that require fewer samples turn on as soon as they are ready, increasing the on-time for the triggers.

Each long rate trigger is controlled by about 30 commandable parameters. These parameters define the relative times of several background periods, the time, duration, and amount to step the phase for the foreground period, the degree of the polynomial to fit, a minimum variance (σ_{\min} , needed for low count rates), a systematic noise level (β , needed for high count rates), a threshold for declaring a trigger ($\sigma_{\text{threshold}}^2$), several parameters that

control the CPU usage, and an enable/disable parameter. The background regions can either be all before the foreground samples (an extrapolation) or can bracket the foreground sample (an interpolation). The CPU usage is controlled in several ways. One can specify which tick of the 64 msec clock that each criterion is evaluated. This ensures that the CPU usage is evenly spread out. There is a CPU usage monitor and if a commandable level is exceeded, triggers will autonomously turn themselves off for a commandable period of time to maintain an acceptable CPU usage.

To obtain the long rate trigger score, one first finds the counts and variance on the counts in the foreground period ($C_{\text{fore}}, \sigma_{\text{fore}}^2$). Second, one fits a function (constant, linear, 2^{nd} order) to the background samples. Third, one integrates the fit function during the foreground sample to find the expected background rate ($C_{\text{back}}, \sigma_{\text{back}}^2$). (We use "model variance", so σ_{fore}^2 is actually based on C_{back}), Finally, the trigger score is calculated as:

$$S = \frac{(C_{\text{fore}} - C_{\text{back}})^2}{\sigma_{\text{fore}}^2 + \sigma_{\text{back}}^2 + \sigma_{\text{min}}^2 + \beta^2 C_{\text{back}}^2} \quad (3)$$

Here, σ_{min}^2 provides a minimum variance to protect against very low counts and β protects against systematic effects at high count rates. When the count rate is very high, the variations will no longer be Poissonian. The presence of β converts the trigger score from a signal-to-noise criterion to a percentage difference criterion. The units on β is percent change per effective σ . At high count rates, the C_{back}^2 term will dominate over the σ^2 terms, and the trigger score becomes

$$S = \left[\frac{C_{\text{fore}} - C_{\text{back}}}{\beta C_{\text{back}}} \right]^2 \quad (4)$$

For example, if the foreground has a 5% net increase over the background and $\beta = 0.025$ (i.e., 2.5%), then the trigger score will be $\approx 2^2$. If one did not have the β term, a 5% net increase would be about 5σ (assuming the BAT background rate) and the trigger score would be 5^2 .

The huge size of BAT means that even a small change in a non-transient, but variable source will appear to be a statistically significant change in the count rate. Sources such as Cyg X-1, Her X-1, and Sco X-1 could easily produce consistent triggers forcing us to raise our thresholds. To guard against this, we will implement a new concept which we call a "veto" trigger. We will use a coded aperture technique based on "URA-tagging" [1] to effectively deconvolve the mask pattern in real time. Each photon is assigned a probability that it came from a designated source location based on whether it could reach the detector through the mask pattern. The sum of the probabilities becomes that source's strength at that time. Although developed for URA patterns, the mask

tagging also works for random patterns such as BAT. Some of the trigger criteria will process the mask-tagged time histories in the same way that the 36 region-energy combinations are processed (i.e., they will be stored as integral sums like equation 2). If the trigger criterion exceeds a threshold, a (commandable) set of regular triggers are disabled for that time period. For example, we might have veto triggers that have foreground durations of 1, 5, and 10 sec that are applied to the tagged time series for Cyg X-1. If any of those veto triggers exceed their thresholds, we disable the 1, 5, and 10 sec long rate criteria. We will have the capability to track up to three mask-tagged sources for the veto system.

We plan space for about 500 long rate trigger criteria. The parameters that control the CPU usage ensures that we will be able to run as many as possible.

IMAGE TRIGGERS

To search for GRBs or other transients on long time scales, we will form images of the FOV and search for new objects. The flight software forms an on-board encoded image every 8 seconds which are used as the background images for the long rate triggers. Those images are combined together on three different time scales (perhaps 64 sec, 10 minutes, half an orbit) and the on-board image deconvolves the mask pattern. (The on-board image process consists of a non-iterative clean to remove known bright sources, a mask deconvolution, and a back project analysis to refine the location.) We search each such image for significant sources and eliminate known sources using an on-board table. Sources that exceed a commandable threshold are declared sources suitable for Swift to slew to.

SUMMARY

The BAT instrument on Swift will have trigger software that can explore a wide parameter space (4 msec to orbital time scales, 4 different energy ranges, subregions of the FOV). All types of triggers (short, long, and imaging) will use on-board imaging to detect false triggers or known steady sources. About 16,000 commandable "knobs" can be used to optimize its performance. Of course to avoid massive confusion, only a few of those will actually be adjusted on orbit. The software will autonomously adjust the number of criteria to maximize the use of the available CPU power.

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