Gamma-Ray Urgent Archiver for Novel Opportunities (GUANO): Swift/BAT Event Data Dumps on Demand to Enable Sensitive Subthreshold GRB Searches

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Abstract

We introduce a new capability of the Neil Gehrels Swift Observatory to provide event-level data from the Burst Alert Telescope (BAT) on demand in response to transients detected by other instruments. We show that the availability of these data can effectively increase the rate of detections and arcminute localizations of gamma-ray bursts (GRB) like GRB 170817 by \( >400\% \). We describe an autonomous spacecraft-commanding pipeline purpose built to enable this science; to our knowledge, this is the first fully autonomous extremely low-latency commanding of a space telescope for scientific purposes. This pipeline has been successfully run in its complete form since 2020 January, and has resulted in the recovery of BAT event data for \( >800 \) externally triggered events to date (gravitational waves, GWs; neutrinos; GRBs triggered by other facilities: fast radio bursts; and very high-energy detections), now running with a success rate of \( \sim90\% \). We exemplify the utility of this new capability by using the resultant data to (1) set the most sensitive upper limits on prompt 1 s duration short GRB-like emission within \( \pm15\text{s} \) around the unmodeled GW burst candidate S200114f, and (2) provide an arcminute localization for short GRB 200325A and other bursts. We also show that using data from GUANO to localize GRBs discovered by other instruments, we can increase the net rate of arcminute-localized GRBs by \( 10\%–20\% \) per year. Along with the scientific yield of more sensitive searches for subthreshold GRBs, the new capabilities designed for this project will serve as the foundation for further automation and rapid target of opportunity capabilities for the Swift mission, and have implications for the design of future rapid-response space telescopes.

Unified Astronomy Thesaurus concepts: Gamma-ray bursts (629); Gravitational wave sources (677); Space telescopes (1547); X-ray telescopes (1825)

1. Introduction

The Burst Alert Telescope (BAT; Barthelmy et al. 2005) onboard the Neil Gehrels Swift Observatory (Swift; Gehrels et al. 2004) is the most sensitive gamma-ray burst (GRB) detector in current operation and the only one that frequently provides arcminute localizations of hard X-ray and gamma-ray transients. BAT has been enormously successful in its main missions of (1) detecting and promptly localizing GRBs with arcminute accuracy (Gehrels et al. 2009) and (2) performing the most sensitive and highest resolution all-sky hard X-ray survey to date (Oh et al. 2018).

The overwhelming majority of BAT-detected GRBs are found using the onboard triggering algorithms (Fenimore et al. 2003), which determine the reality of a triggering event by both comparing the detector event rates and by constructing a sky image and searching for significantly detected \( (>6.5\sigma) \) new point sources. However, despite the success of the BAT onboard triggering algorithm, BAT can detect GRBs that do not trigger the onboard algorithm. We must rely on ground searches that run on downlinked BAT data to search for these untriggered GRBs. However, the utility of the BAT to search for events that did not trigger onboard (untriggered, or subthreshold) has been limited because event-level data on the ground are not available. This is unfortunate, as despite its limited field of view (\( \sim7000\text{ sq. degrees} \)) in comparison to, e.g., Fermi/GBM (Meegan et al. 2009), the superior sensitivity of the BAT in principle allows access to weak sGRBs that would otherwise be undetectable by other missions, and its arcminute localizing power is critical to rapid follow-up of these events. The unavailability of the event data for ground searches has also necessitated the development of BAT trigger simulators (Lien et al. 2014; Graff et al. 2016) in order to perform population inference of the cosmic GRB population, corrected for the complex selection functions/biases of the BAT onboard triggering algorithms.

In normal operations, BAT records the arrival time (to 100 \( \mu \text{s} \) accuracy), location (in detector coordinates), and energy (in one of 80 bins from 15 to 350 keV) for each individual count that strikes the detector. These data are referred to as event-by-event (or simply: event) data. Because of the large effective area of the BAT, the data volume produced is quite large, and cannot all be stored onboard or telemetered to the ground. For this reason, the BAT has relied on the performance of its onboard real-time detection algorithms, and only preserves event data and telemeters them to the ground around the time of events that trigger these onboard algorithms.

If there is no triggered event for a certain time period, the only BAT data products available for analysis on the ground are summed-array rate light curves (in 64ms, 1 s and 1.6s\(^6\) bins in four energy channels), 64 s single-bin (15–50 keV) images, and...
and 300 s 80-bin images for use in the all-sky survey. While bright GRBs can be identified in the rate data, event-mode data are necessary to construct sky images for localization, to remove the hard X-ray and particle background, to identify and remove the effects of glitches or noisy individual detectors, and for the creation of background-subtracted light curves for individual sources. Importantly, the complete event-mode data are necessary to reliably distinguish between detector noise and real dim/subthreshold GRBs. (DeLaunay et al. 2020, in preparation).

In order to assess the capabilities of the BAT onboard triggering algorithms versus those achievable if the event data were available on the ground, we choose as an example the one known gravitational wave (GW)/GRB event to date, GRB 170817 (Abbott et al. 2017). GRB 170817 was not detected by BAT, as unfortunately the burst location was occulted by the Earth at the time of the GW and GRB (for more details see Evans et al. 2017).

We model the light-curve shape of GRB 170817, and take the best-fit spectral parameters, \( E_{\text{iso}} = -0.62 \) and \( E_{\text{peak}} = 185.0 \text{ keV} \) measured from the Fermi/GBM observation (Goldstein et al. 2017). Using the BAT trigger simulator software (Lien et al. 2014), and setting the number of active detectors in the BAT array to \( N = 18,000 \), we introduce realistic background on top of the light curve, and then simulate the BAT triggering response as a function of position in the BAT field of view (FOV). The simulated BAT light curves and the triggering result are shown in Figure 1. At its distance of 43 Mpc, GRB170817 would have resulted in an onboard trigger at >18 sigma significance if it were \( \leq 30\text{deg off the boresight of BAT} \) (corresponding to a partial coding of at least \( \sim 50\% - 60\% \) depending on the BAT orientation).

We repeat the exercise, this time simulating a GRB 170817-like burst at various distances to assess the triggering range. The maximum distance at which a GRB 170817-like burst would likely trigger BAT onboard is found to be \( \sim 67 \text{ Mpc} \) for the most favorable observing scenario of the burst occurring at 100% partial coding. This should not be taken as an average range, only a maximum one, as most other locations within the BAT FOV will have reduced ranges compared to this. To provide context with respect to other GBM missions, GRB 170817 would not trigger Fermi/GBM onboard beyond 50 Mpc (Goldstein et al. 2017), and would not be detectable by the GBM targeted search ground analysis beyond \( \sim 74 \text{ Mpc} \) (Kocevski et al. 2018).

However, if the BAT event data are available on the ground, more sensitive targeted searches can be run around the time of the GW events. Using a likelihood-based targeted search (see DeLaunay et al. 2020, in preparation, and Section 6.1.2 of this work), we find that a GRB 170817-like burst can be recovered out to a distance of \( \sim 100 \text{ Mpc} \) if it were at the center of the FOV and out to \( \sim 71 \text{ Mpc} \) if it were 45deg off the boresight of BAT. Weighting the average range achievable over the entire coded FOV with the event data available on the ground versus that from relying on onboard triggers, this range increase corresponds to a volumetric rate increase of \( >400\% \) for the detection, and arcminute localization, of GRB 170817-like bursts.

In addition to dramatically extending the range and thus volumetric rate of detections (and importantly, arcminute localizations) of GRB 170817-like bursts, the availability of event data on the ground would also increase the rate by a further \( \sim 15\% \) by correcting for the duty-cycle limitations of BAT. Swift spends \( \sim 15\% \) of its time slewing from target to target. During these times, the BAT onboard trigger algorithms are not run. However, GRBs can be found and localized during slews using the event data on the ground (see, e.g., Copete 2012 and Section 7 of this work) with little to no decrease in the sensitivity to short bursts.

The rate enhancements of detection and arcminute localization of GRB 170817-like bursts are only possible with the event data available on the ground, and clearly motivate extraordinary efforts to recover these data. The development in 2012 of the capability to save all of the continuous time tagged event (CTTE) data from the Fermi/GBM instrument was critical to the development of powerful ground analyses that extend their range for targeted searches, and that now recover an extra \( \sim 40 \) short GRB candidates per year (Kocevski et al. 2018) that do not trigger Fermi/GBM onboard. Bringing all of the event data down is not an option for Swift given the higher effective area (and thus count rate) of the BAT and the fact that, unlike Fermi, Swift does not have a high-gain antenna. So we are limited by both telemetry load and bandwidth.

Instead, in this paper we describe a newly developed capability for Swift to save the event-mode data on demand, in response to a trigger from an external instrument, and rapidly telemeter it to the ground for use in new powerful targeted subthreshold GRB searches, especially with application for the search of coincident GW/GRB events (but also for other trigger types, see Section 5).

In Sections 3–6 we describe relevant technical, design, and implementation details of the GUANO pipeline, and evaluate its performance to date. In Sections 7 and 8 we provide some direct examples of scientific results derived from data recovered by this pipeline.

### 2. BAT Ring Buffer

The event-mode data are stored in a ring buffer on the BAT instrument computer, which overwrites itself when it reaches approximately 23 million counts. While the average BAT full-detector count rate is in the range of \( \sim 8000 \text{ cts s}^{-1} \) as of 2020, the effective lookback time (how long before any given piece of event-mode data is overwritten) varies on short timescales due to the varying full-detector count rate (from varying background levels throughout the orbit, GRBs, bright X-ray
sources, and detector noise), and on the timescale of years due to the gradual decrease in detector effective area over time. These varying factors and their impact are shown in Figure 2.

In order to save the event data of interest, they must be moved from the ring buffer to the solid-state recorder (and marked for downlink) before being overwritten, which can only be performed by sending a command to perform this task to Swift. For this reason, extremely low-latency commanding of the spacecraft (with a maximum, but varying, latency of ~25 minutes) is required in response to an external trigger (GW, neutrino, GRB, etc).

### 3. South Atlantic Anomaly

During passage of the South Atlantic Anomaly (SAA), <10% of the time, the BAT instrument does not record information on individual photon events due to the extremely high count rates.\(^8\) For this reason, any event trigger occurring while Swift is passing through the SAA will not have any event data recorded. However, the location of the SAA boundary is not hard-coded into the BAT instrument (for Swift’s narrow-field instruments, and the Fermi instruments, the SAA definition is a coordinate-defined polygon). Instead, BAT determines whether it is in SAA-mode dynamically, determining entry to SAA based on the size of the current onboard data-processing backlog, and exit from SAA-mode based on the instantaneous count rate recorded.

The physical SAA boundary and extent is dynamic on short timescales, responding to space weather and events like coronal mass ejections from the Sun (Fürst et al. 2009). In addition to this, using 15 years of Swift telemetry, we have determined that the average spatial extent of the SAA according to BAT has changed significantly over time, meaning that any definition of the SAA boundary needs to be calculated from recent data. For the purposes of the GUANO pipeline, we therefore calculated a region, shown in Figure 3, which is used for screening times of triggers that occurred during SAA passage. This region is defined by the latitude/longitude distribution of Swift at times when the BAT was in SAA-mode in 2019.

### 4. GUANO Pipeline

Here we briefly outline the entire GUANO pipeline. A detailed flowchart depiction of the pipeline and relevant external processes is shown in Figure A1.

#### 4.1. The BAT Ring Buffer Dump Command

The command sent to the spacecraft and BAT to save any existing event data in a certain window around a given timestamp is called a BAT ring buffer dump (BRBD) command. This command has various configurable parameters. For the purposes of the GUANO pipeline, the majority of these parameters are fixed (e.g., event data from which parts of the detector array to save, and what types of event data) and the only configurable ones are the start time of the requested event window, duration of the requested event window, and which virtual channel (VC) in the solid-state recorder (SSR) the data should be copied to. The VC controls the latency/priority of sending the data to the ground.

Given the configurable start time and duration of the requested event window in a BRBD, triggers that are temporally adjacent (but not necessarily related) can be merged by the GUANO pipeline into a single BRBD command to optimize the use of commanding resources and ensure the recovery of all the relevant data.

The ultimate goal of the GUANO pipeline is to get a BRBD command with the best parameters to the spacecraft, and to execute on the BAT onboard computer, before the relevant data are overwritten in the ring buffer and are lost forever. Ensuring the success of this mission, and the safety of Swift as a whole.
in the process, requires a complex real-time system with several interacting components.

4.2. Commanding Opportunities

As is typical for space telescopes (especially those in low Earth orbit), the Swift Mission Operations Center (MOC) is not in constant two-way contact with Swift. Sending commands to the spacecraft requires a commanding opportunity, typically called a contact or a pass. There are two such types of commanding opportunities capable of contacting Swift: Utilizing prescheduled passes via one of the ground stations used by Swift; and on-demand through the Tracking and Data Relay Satellite System (TDRSS). Swift performs on average nine ground-station passes per day, which means that fewer than one in six triggers on average can be successfully commanded using existing ground-station passes.

The ability of the Swift MOC to autonomously schedule a TDRSS commanding contact on demand was developed specifically for GUANO, as it is necessary for the recovery of ∼80% of triggers. Previous to this development, the latency of manual on-demand TDRSS scheduling and commanding was 25 minutes at least, and in reality often much longer, and because it required manual operation, could not be performed with acceptable latency after hours as the Swift MOC is only staffed during working hours. This new capability also opens the door to lower latency target of opportunity observations with Swift.

However, this comes with a few limitations. First, the required latency for requesting a TDRSS contact under this system is currently 14 minutes, meaning that a contact cannot be requested to begin any sooner than 14 minutes in the future. Second, resource demands on the TDRSS network by other users and missions means that occasionally, there is no availability of the requested TDRSS resource.

4.3. Checks

The extremely low-latency commanding required to save the data necessitates an autonomous pipeline. A dedicated listener waits for an event (via either GCN notice or private channel) that meets the triggering criteria. Upon reception, it performs a series of checks:

1. At the time of the event, was Swift in the SAA? (∼9% of triggers fail this check.)
2. If there is a localization associated with the event, was any part of the localization region above the Earth limb with respect to the spacecraft at the time of the trigger (and thus capable of depositing flux onto the detector array)? (∼30% of triggers with localization information fail this check.)
3. Was there a BAT trigger coincident with the trigger time (as BAT will dump event data anyway in this case)?

If it passes all of these checks, it is approved for commanding, and the trigger is placed into the scheduling queue.

4.4. Queue Scheduler

Sending BRBD commands based on astrophysical triggers requires careful handling of latencies, priorities, and overlaps. Each triggering event typically has two parameters that determine its priority. First, some measure of the “goodness” of the event, in most cases, this will be a so-called false-alarm rate (FAR), typically given in units of Hertz, where a lower FAR is given priority over a higher one. The FAR values associated with each event come from the triggering instrument (LIGO/Virgo, IceCube, HAWC, etc.). The second prioritization is the trigger time of the event, which currently is only used to determine if an event should be uploaded, based on its likelihood of still having the relevant data in the ring buffer when dumped.

Trigger handling must be dynamic, and adaptable to changing priorities. For example, when an event occurs, we will associate a pass with it (either a ground-station pass, or request a TDRSS contact). However, if a newer, better (e.g., lower FAR) arrives after the first event, but before the scheduled pass, we preferentially should upload that on the pass, and then the first event becomes a secondary priority. A final decision as to exactly which data to dump must be made 2 minutes before the start of the commanding pass. As currently only a single BRBD command may be sent per commanding pass, it is important to not only prioritize the best triggers, but also maximize our chances of dumping all the event data necessary to perform the analyses for every trigger possible.

In order to handle triggers and uploads correctly, we developed a simple queue scheduler for triggers. When there are BRBD triggers in the queue that have not been uploaded, the queue scheduler first checks whether there is an upcoming prescheduled ground-station or TDRSS commanding opportunity that is within the projected ring buffer lookback time. If no suitable pass is scheduled, a TDRSS forward service is automatically requested via the Space Network Access System (SNAS) EPROM interface to begin in the lowest latency allowable by the Space Network.

If there is a pass available, either prescheduled or requested, on which to upload a BRBD command, the pass is assigned to this BRBD. If the pass is fewer than 2 minutes away, the queue scheduler creates the most appropriate BRBD command (optimizing the parameters to cover more than one trigger if possible), transfers it to be uploaded to Swift, and marks the commanding pass as used, and the BRBD entry in the queue as uplinked.

These steps are repeated for all recent triggers (<30 minutes old), every 20 seconds. The queue system has no memory of the previous decision that was made, other than requested TDRSS contacts, and the previously uplinked BRBDs, so that if more triggers arrive, then their upload strategy is fully reevaluated to optimize the chance of recovery of all requested data, and if necessary, further commanding contacts will be scheduled to upload multiple commands.

Ring-buffer dumps have a maximum length of 200 s, and a default minimum of 90 s, so in the case where two triggers can be covered by a single dump, we merge them together into a single command. Our requirement is that we dump 90 s of event data for each GW event (to provide suitable duration of time around a putative short GRB to allow the background to be modeled), so with a maximum dump length of 200 s, this means that we can dump the event data associated with two or more external triggers with a single command if the maximum and minimum event times are less than 110 s apart.9 Triggers that cannot be merged in this way are sent as single BRBD commands.

9 This maximum duration of 200 s is not necessarily a hard limit, and work is ongoing to extend this.
Scheduling of TDRSS command passes, although automated, can sometimes fail due to issues with limited resources of the Space Network. When a TDRSS pass is scheduled, we receive a notification that the scheduling has been successful. However, due to a quirk in the implementation, we do not receive a notification if the scheduling was not successful. However, we have empirically determined that for 90% of cases, we receive notification of success in <5 minutes. If more than 5 mins has passed without notification that the TDRSS pass has been scheduled, the queue scheduler assumes that the pass has failed, and will mark the pass request as timed out. In this case, the GUANO scheduler will reevaluate the upload strategy, and either use a ground-station pass or request another TDRSS.

**5. Performance of the GUANO System**

The first successful BRBD command in response to a scientific trigger was sent to Swift on 2019 April 8, triggered by the LVC detection of GW candidate S190408an (LIGO Scientific Collaboration & Virgo Collaboration 2019), tentatively classified as a binary-black hole (BBH) merger. At this time, the ingestion of triggers was automatic, but the entire scheduling and commanding sequence was manual, resulting in a strong working-hours duty cycle onto the success rate. If a trigger arrived during MOC working hours, its associated BRBD had a ~70% chance of success, whereas the success rate for after-hours (two-thirds of the weekday and the entire weekend) was near zero, resulting in a very low average recovery rate. As technical hurdles involved with reducing command latency and automating various parts of the pipeline were overcome, the recovery rate increased apace, eventually reaching near 90% recovery after the final key components of the GUANO system were implemented in early 2020. An annotated figure showing the recovery rate as a function of time/GUANO development is presented in Figure 4.

While the recovery rate is determined entirely by command latency, the actual latency requirement varies due to the changing rate of counts hitting the detector and filling up the ring buffer, as described in Section 2. On short timescales, variations in the ring buffer lookback time are strongly dependent on the geographical location of Swift in its orbit. Close to the SAA, where the background is higher, the effective duration of the ring buffer is shorter. In addition, the number of noisy pixels active in the detector also strongly affects the lookback time, and thus infrequent calibration activities on the BAT detector can impact recovery rates for a few hours afterward. This can be made more clear by examination of Figure 5. As can be seen, while the majority of commands received onboard with a latency under 20 minutes are successful in recovering the data, a small fraction are not, due to the effects discussed above. Commands shown just below the red margin line arrived onboard Swift only a few seconds too late to recover the data. The latency cutoff where recovery is successful 99% of the time is ~16 minutes. The cluster of BRBD commands at ~17 minutes shows the average latency GUANO achieves in its current configuration. We stress that these 17 minutes include all latencies on the part of both the triggering instrument and the distribution of the notice to the Swift/MOC. GUANO is typically triggered 30–120 seconds after the astrophysical T0, depending on the various latencies of the triggering instrument. Work is ongoing to continue to decrease the GUANO latency. The lowest achieved latency to date was a BRBD command that was uplinked to Swift ~2.5 minutes after the T0 of the astrophysical trigger.

While the GUANO concept was originally motivated by targeted searches for subthreshold GRBs around the times of GW detections in particular, we eventually opened the system to a larger array of transient types. The type distribution of triggers GUANO has processed and recovered event data for as of publication are shown in Figure 6.
We provide a public webpage (https://www.swift.psu.edu/guano/) that updates live as data are received on the ground, where pointers to the data recovered for each public triggering event can be found.

In the following sections, we provide example results from just a few out of the >800 windows of BAT event data around astrophysical triggers recovered by GUANO to date.

### 6. LIGO/Virgo Unmodeled GW Burst Candidate S200114f

On 2020-01-14 02:08:18.23 UTC, the coherent Wave Burst (cWB) pipeline (Klimenko et al. 2016) running on real-time data from the Livingston, Hanford, and Virgo detectors of the LIGO/Virgo observatories triggered on an unmodeled transient candidate, S200114f. (LIGO Scientific Collaboration & Virgo Collaboration 2020). Notice of this event was received by the Swift MOC via private pipeline from the LVC before public distribution\(^\text{10}\) of the first notice, and triggered GUANO. The relevant timeline is described in Table 1. Note that the GUANO pipeline for S200114f is atypical, as no TDRSS scheduling or commanding was necessary for this event due to the serendipitous temporal coincidence of a ground station with Swift’s ground track within the necessary latency window.

At the time of the GW detection, the Swift narrow-field instruments (and hence the BAT boresight) were pointed at the Fermi/LAT source 4FGL J0535.3+0934. This source is located within the 90\% localization containment region for S200114f, and thus the BAT FOV covered >99.7\% of the GW localization region at T0, shown in Figure 7.

This high coverage fraction, coupled with the event data saved by the GUANO system, allow very sensitive and complete upper limits to be placed on the existence of prompt GRB-like emission from S200114f. We set such limits below, and throughout also demonstrate the various techniques and results that the event data allow.

\(^{10}\) Through the low-latency LVC-Swift Memorandum-of-Understanding (MoU) pipeline Swift receives notice of possible GW triggers as soon as information is available to enable GUANO.

### 6.1. Detection and Localization of Weak Short-duration Transients

#### 6.1.1. Image Analysis Results

With event data available, it is possible to create sky images in specific energy and time ranges. With the Swift FTOOLS\(^\text{11}\) task batbinevt, the event data can be accumulated into detector-plane images (DPI), which are used to make sky images with the task batfftimage. When searching for a short transient, it can be helpful to create a sky image using a background-subtracted DPI, where the background DPI is made from the event data at times either immediately before or after the time window of interest. This helps remove coded noise from bright point sources and the diffuse background, but would subtract out signal if the signal was also present during the background time. Point sources in the sky images can be searched for using the task batcelldetect, which outputs a catalog of the discovered sources along with several optional outputs, including a sky image of the measured Gaussian noise. We use this noise map to set position-dependent fluence upper limits over the duration of the image.

For S200114f we set upper limits for two durations both in the 14–195 keV energy range: a 10 s duration starting 2 s prior to the event time, and an 88 s duration centered on the event time. For the 10 s duration we use a background-subtracted DPI to be more sensitive to a transient that starts after the end of the background DPI (10 s prior to the event time). For the 88 s duration we do not use a background-subtracted DPI so that we do not lose sensitivity to a transient that may have started prior to the earliest data we have available during this pointing. For each of the durations we find the average upper limit in BAT counts weighted by the localization probability of S200114f at that position in the sky and convert it into a fluence assuming a power law with an index of $-1.32$ (typical for short GRBs in the BAT band; Lien et al. 2016) using the online WebPIMMS\(^\text{12}\) tool. We found $8\sigma$ fluence upper limits over 14-195 keV of $4.1 \times 10^{-7}$ erg cm$^{-2}$ for the 10 s duration and $1.1 \times 10^{-6}$ erg cm$^{-2}$ for the 88 s duration.

#### 6.1.2. Max Log Likelihood Results

The availability of event data on the ground lets us explore analysis methods that take more computational power than can be achieved onboard. One such method is a maximum likelihood-based search (for more details, see DeLaunay et al. 2020, in preparation). This search uses a Poisson likelihood of the expected counts from background plus a signal model in each of the detectors for several energy bins, and maximizes over the signal model parameters, which include spectral shape, intensity, and sky position. The background model is fit using data outside a temporal search window; here $+/-15$s around the event time is searched. Inside the temporal search window, the search is performed for durations of 0.256 s, 0.512 s, 1.024 s, and 2.048 s. The significance of a transient point source is measured using a test statistic (TS):

$$TS = -2 \log \left[ \frac{P(data|H_{S=0})}{P(data|H_{S})} \right].$$

\(^{11}\) http://heasarc.gsfc.nasa.gov/f tools

\(^{12}\) https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3pimms/w3pimms.pl
where $H_B$ is the background-only model, and $H_{S+B}$ is the best-fit signal-plus-background model. The square root of the TS is a comparable measure to a signal-to-noise ratio ($S/N$).

The sensitivity of this search is a function of the background rates and the source position in the FOV. To find the flux sensitivity to a particular event, we inject a simulated signal into the event data and run the search to see if we recover the injected signal above a certain significance. We do this many times at several flux strengths and positions across the FOV. Then, at each position we find at which flux we recover 90% of signals at a $\sqrt{TS} > 8$. The signal injections are made at random times inside of the search window and using the detector response for the simulated source position. For the search around S200114f, we find the 14-195 keV flux sensitivity assuming a power-law index of $-1.32$ and averaged over its localization probability for both 0.256 s and 1.024 s timescale transients as $2.1 \times 10^{-7}$ erg cm$^{-2}$ s$^{-1}$ and $8.1 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$, respectively.

### 7. Localizing GRBs Discovered by Other Instruments

In addition to the utility of the BAT event data to perform the most sensitive searches for GRB emission associated with transients detected in other wavelengths and messengers (as in the previous section), the availability of these data via GUANO also allows BAT to provide arcminute localizations for GRBs that otherwise have no or extremely large localizations.

The majority of detected GRBs are reported by Fermi/GBM and INTEGRAL/SPI-ACS. In the case of Fermi-detected GRBs, the localizations can range from $\sim$100 sq. degrees to thousands of square degrees. In the case of INTEGRAL/SPI-ACS, there is no localization information at all. As a result, without a BAT co-trigger, these bursts almost always have no identified afterglows and lack the attendant science that comes with follow-up observations, including redshift measurement, energetics, jet structure, circum-merger density, etc.

Generally, if a GRB that triggers Fermi/GBM or INTEGRAL/SPI-ACS occurs within the BAT FOV, it also triggers

#### Table 1

**Timeline of Events for S200114f**

| Time (T0) | Event Description |
|-----------|-------------------|
| 02:08:18  | S200114f reaches Earth. |
| 02:50     | cWB pipeline identifies S200114f in the LVC data stream. |
| 02:55     | Swift MOC receives alert, and triggers GUANO. |
| 03:30     | Trigger passes vetting, and is placed in GUANO queue for uplink. |
| 04:00     | GUANO determines that there is a serendipitous ground-station commanding pass within T0 + 25 minutes, and hence no need for a TDRSS contact. |
| 24:00     | GUANO passes command to commanding computers for uplink via the Malindi ground station. |
| 26:30     | BRBD command uplinked to spacecraft. |
| 26:31     | BRBD command executes onboard BAT computer, data successfully moved from ring buffer to the Solid State Recorder, and marked for high-priority downlink. |
| 01:50:00  | Event data arrive on the ground for analysis. |

**Note.**

* If another event had arrived and triggered GUANO while it was waiting to uplink the BRBD command for S20014f, it would then have autonomously scheduled a TDRSS contact and determined which event to upload first based on their FARs, see Section 3.

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Figure 7. The instantaneous coverage of the Swift/BAT FOV at GW T0 is shown in green, along with the localization region, and 50/90% containment contours of S200114f in red and black. The BAT FOV covered >99.7% of the GW localization region at T0.
the BAT onboard, with the normal Swift GRB response. However, this is not always the case. While BAT is a priori more sensitive than these instruments and thus regularly triggers on even weaker bursts, a variety of factors (sometimes combined) can result in a GRB detected by other instruments that does not trigger BAT onboard, even though it originates from within the BAT FOV.

1. The BAT onboard algorithms are limited by the necessity to run analyses in real time on limited processors and thus are not able to reach 100% of the recovery potential that can be achieved on the ground with the same techniques.
2. The BAT onboard algorithms do not run while Swift is slewing, which is \(~\sim 15\%\) of the time.
3. The GRB, while it may be intrinsically bright, is incident upon BAT from a line of sight for which the BAT coding fraction is very low (read: near the edge of the FOV), and undetectable using the conventional BAT analysis techniques, necessitating instead complex analyses such as the max-log likelihood search described in Section 6.1.2.
4. The GRB may be extremely spectrally hard, with very weak emission in the BAT bandpass.

By recovering BAT event data around the times of GRBs discovered by other missions, we can close this gap when possible and fully exploit the localizing power of BAT.

Since opening the GUANO listener to GRBs in mid-February 2020, GUANO has recovered BAT event data around the time of a large majority of the GRB triggers from Fermi/GBM, INTEGRAL,\(^1\) and CALET that do not also trigger BAT. Of these, arcminute localizations for four GRBs have been recovered using the BAT event data provided by GUANO, at a rate of approximately two per month: GRBs 200216A (DeLaunay et al. 2020a), 200228A (Tohuvavohu et al. 2020), 200325A (DeLaunay et al. 2020b), and 200405B (DeLaunay et al. 2020c). This rate and the analysis of historical BAT FOV overlaps with GBM localizations leads to the conclusion that GUANO can effectively increase the worldwide net rate of arcminute-localized GRBs by at least 15 GRBs per year, an increase of 17% over the current rate. Of these four GRBs, the reasons they did not trigger BAT onboard were the following:

1. One because Swift was slewing at the time of the GRB.
2. One due to an inefficiency in the onboard trigger algorithms. In this case, the BAT onboard algorithms only made and searched for sources in images in the 100-350 keV bandpass around the time of this burst, whereas the source was found on the ground when lower energy events were included.
3. Two because they originated from a location on the sky with a very low partial coding fraction, and thus were too intrinsically weak in the sky images to be found using the standard BAT analysis, both onboard and on the ground.
4. One because an inelastic collision with a high-energy particle in the instrument shield may have caused the GRB.

Here we outline the GUANO-enabled localization of one of these bursts, short hard GRB 200325A.

7.1. GRB 200325A

GRB 200325A was discovered in real time by Fermi/GBM (Fermi GBM Team 2020), INTEGRAL/SPI-ACS, and

\(^{13}\)GUANO also triggers on the weak/subthreshold stream from INTEGRAL/ISGRI, whose astrophysical purity is unknown (Higgins et al. 2017). None of these triggers have been seen in BAT to date.

Figure 8. A 25 ms binned full-detector summed light curve of GRB200325A, constructed from the event data recovered by GUANO. Because the GRB originated at such low partial coding, the full-detector summed light curve shown here (not background subtracted) is much more significant than the mask-weighted light curve (background subtracted), as more counts from this GRB arrived at the detector after penetrating the instrument shield through the sides than those that passed through the mask openings.

AGILE/MCAL (Ursi et al. 2020) with T0 of 2020-03-25 03:18:31.7 UT. Detections were also later reported by AstroSat CZTI (Gupta et al. 2020), Konus-WIND, GRS-Odyssey, and HEND-Odyssey (Hurley et al. 2020). Of these instruments, only Fermi/GBM was capable of independently localizing the GRB. It provided a 3σ containment region of \(\sim 800\) square degrees. Swift/BAT did not trigger on this burst.

The low-latency notices of this GRB from Fermi (distributed at T0+8s) and INTEGRAL (distributed at T0+44s) both triggered GUANO. The GUANO queue scheduler merged these triggers into a single specific BRBD command, requesting 200 s of event data from \([-50, +150]\) around T0, and ensured its uplink by scheduling and confirming an on-demand TDRSS contact within the required latency window. GUANO then sent the BRBD for uplink to Swift. The BRBD command executed onboard the BAT computer at T0 + 13 minutes, moving the requested data from the ring buffer to the solid-state recorder, and marking it for high-priority downlink. The requested data arrived on the ground at T0 + 46 minutes.

The GRB was clearly detected in the BAT detector summed light curve; see Figure 8. We used the Swift FTOOLS task batbinevt to accumulate the event data into DPIs, and then
made these into sky images with the task \texttt{batfftimage}. The sky images were created using a background-subtracted DPI using event data from directly before the GRB interval. The sky images were then processed with the task \texttt{batcelldetect} to search for sources. The DETECTION mask was used in order to search out to the largest solid angles/lowest possible partial coding. Successive manual trials were performed, optimizing both the “source” and “background” intervals, as well as the energy range for the DPI and sky-image accumulation, until we were able to produce a sky image with a source >7σ. The burst location was found in an image made with an interval from −0.064 s to 1.024 s, and with events in the energy range 20.0–195 keV, with an S/N of 7.5 from \texttt{batcelldetect} and at an extremely low partial coding fraction of 8.2%; see Figure 9. This very low partial coding, and thus the need to fine-tune the source interval and energy ranges for a construction of a sky image with an acceptable S/N, explain fully why the BAT onboard algorithms did not trigger on this burst. However, the repeated optimization of the images induced significant trials onto the detection.

Simultaneous to the image analysis, the computationally expensive maximum-likelihood-based search (DeLaunay et al. 2020, in preparation) was also run on the BAT event data at the time of this burst. This search returned the same source as the image analysis, with no iteration or fine-tuning required, and at a much higher significance with a \(\sqrt{TS} \) of 21.7.

We distributed a GCN circular reporting the localization to the community (DeLaunay et al. 2020b). The burst coordinates are 31.7203, −31.816 with a 90% containment on the uncertainty (systematic plus statistical) of 4 arcminutes. Unfortunately, this location was too close to the Sun to allow any follow-up to search for an afterglow.

Approximately a day after we reported this arcminute localization, the Inter-Planetary Network localized the burst via intersecting timing annuli with KONUS-Wind, Mars Odyssey-HEND, Fermi/GBM, and INTEGRAL SPI-ACS. Their 90% localization region spanned 2023 square arcminutes (Hurley et al. 2020) and agreed with the Swift/BAT-GUANO-derived position. The various localizations for this burst are shown in Figure 10.

7.2. Nonimaging Localizations and Out-of-FOV Science

The event data recovered by GUANO can also be used to help localize a GRB even if that GRB does not originate from within the BAT-coded FOV. High-energy photons from GRBs originating from anywhere on the unocculted sky (in low Earth orbit, about one-third of the sky is occulted by the Earth) can penetrate the Z-shield surrounding the BAT instrument or even the entire spacecraft body, and deposit counts into the BAT detector. Indeed, \(~40\%\) of IPN-reported (read: bright) GRBs are also found in searches of BAT rate light curves, but originate from outside the coded FOV. With some notable exceptions (e.g., the magnetar hyperflare of SGR 1806–20, one of the earliest bursts of the Swift mission; Palmer et al. 2005), these rate data for out-of-FOV GRBs have typically not been of particular scientific use, except for confirming the reality of a detection, for the following reasons:

1. The rate data (maximum temporal resolution of 64 ms) is not normally of high enough temporal resolution to allow BAT to participate in IPN timing localizations.
2. The rate data are only available in four broad energy bands.
3. The lack of calibrated responses for out-of-FOV lines of sight typically preclude using these data for spectral analyses or any other type of analysis beyond crude examinations of the light-curve morphology.

The on-demand event data from GUANO effectively solve the first two of these issues. Indeed, the GUANO-enabled event data have already allowed BAT to participate in IPN timing localizations of several GRBs (e.g., Svinkin et al. 2020a, 2020b). In addition, the ability to clean noisy/hot detectors and glitches out of the rate data using the event data from GUANO allows for more confident claims of detection of out-of-FOV bursts, and can thus allow BAT to reduce the localization region of Fermi/GBM bursts by ruling out parts of the sky that were occulted for Swift, as in the case of GRB 200307A (Goldstein et al. 2020).

The converse is also true: a nondetection of a GRB in the ground analysis of GUANO-derived event data can rule out the GRB origin from within the BAT-coded FOV. The BAT FOV often overlaps substantial fractions of the Fermi/GBM localization, even for bursts that BAT does not trigger on. For some of these (i.e., GRB 200325A, above, and others) the burst is eventually found within the BAT FOV. However, in cases where the source is not found using the powerful ground analyses, this overlap region can be ruled out and the size of the localization for the burst effectively reduced, often dramatically. From simulations and an analysis of archival data, we predict that using such a technique, BAT can reduce the size of Fermi/GBM localizations by 50% for at least \(~15\) GRBs per year.

With regard to item 3: The event data from GUANO could even be used to characterize, validate, and build response functions for BAT along many different out-of-FOV lines of sight, and thus allow these data to be used in the future for spectral fits, or even for a rough localization in the scheme of, e.g., Fermi/GBM Team (Goldstein et al. 2019; where an astrophysical spectrum is assumed, and then the localization fit from that) or BALROG (Burgess et al. 2017; where the spectrum and localization are fit simultaneously). We note that even for lines of sight \(>100\) degrees away from the BAT boresight \((>50\) degrees outside the coded FOV), the BAT

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure9.png}
\caption{A BAT hard X-ray sky image of GRB 200325A, showing its proximity to the absolute edge of the FOV and the growth of image noise close to the edge. For such sources, and weak sources generally, the max-log likelihood analysis described in Section 6.1.2 is required to distinguish real astrophysical sources from noise.}
\end{figure}
effective area is still hundreds of cm$^2$ at energies $>$100 keV (Palmer et al. 2005), comparable to the effective area of Fermi/GBM. Extending the calibrated responses out to such angles would result in BAT data products (e.g., spectra, possible rough localizations) being usable, beyond just the timing localization and light-curve morphology described above, for many more GRBs per year.

A possible approach would be to take the known spectrum of a Fermi/GBM burst that is seen in BAT from outside the FOV, and jointly fit that spectrum with the observed spectrum from the GUANO event data, and thus generate a response function for that particular line of sight, effectively building a response in a data-driven way, and iterate for each line of sight for which a GRB exists. Alternatively, the data could be used to validate the predicted response from the Swift Mass Model, a pre-launch GEANT4 model of the BAT instrument and the Swift spacecraft body that was used in Monte Carlo simulations to generate detector response matrices for BAT pre-launch, but whose out-of-FOV responses have not been extensively validated due to the previous absence of data.

Such a project is large and well beyond the scope of this work, but we comment that GUANO-dumped event data for GRBs originating from outside of the FOV, but with known spectra from other instruments (e.g., Fermi/GBM) are now accumulating at the rate of approximately a few lines of sight per week, already having accumulated many such bursts as of publication. The Fermi/GBM response is sampled from 272 lines of sight (Connaughton et al. 2015).
8. Conclusions

The ability to recover event data from the BAT instrument on demand significantly increases its sensitivity to weak transients that do not trigger onboard, as would be the case for an off-axis GRB at typical BNS ranges achievable by the ground-based gravitational wave interferometers, effectively increasing the rate of detections and arcminute localizations of GRB 170817-like bursts by >400%. The data can be exploited in various ways to accomplish this, as they enable the creation and search of background-subtracted gamma-ray sky images, the use of new statistical techniques designed to fully exploit the latent information associated with each individual count, and the confident identification, classification, and removal of glitches and GRB-mimickers from the data.

Using just a small fraction (~200 s) of the total BAT event data recovered by the GUANO pipeline (~75 Ks) to date, we demonstrate its utility directly by providing the deepest upper limits on prompt GRB-like emission associated with the GW burst candidate S200114f, and show how the data can be used to recover an arcminute localization for GRBs triggered by other missions, such as short GRB 200325A. We provide a public website\(^{14}\) that records and reports the event data saved in response to public triggers and makes these data fully available to the community for use. Indeed, the data have already seen use by the broader community, beyond what it was designed for, in the Inter-Planetary Network.

In addition, the novel operational capabilities described here, developed as they were necessary to recover these data, demonstrate the first fully autonomous, on-demand, extremely low-latency commanding of a space telescope based on astrophysical triggers. These capabilities open the door to other high-impact science, including fully autonomous extremely low-latency repointing of Swift for target of opportunity observations with its narrow-field instruments.

The development of the capabilities demonstrated by GUANO could have a profound effect on the operational capabilities of future space missions, as well as enhance the science capabilities of Swift. For example, when developing new missions, the cost and associated risk of creating novel flight software to make spacecraft react autonomously to transient triggers is often beyond the scope and budget allowed. In addition, the costs of running mission operations for future missions is significantly higher if out-of-hours human response is required. By developing a system to both automate the ingestion, rank ordering, and validating of transient triggers from multiple sources, combined with an automated way to generate and send the relevant commands to respond to those triggers to the spacecraft, it now becomes possible to build 24/7 response to transients into low-cost missions, as well as larger mission concepts with ultra-low-latency ToO requirements.

We encourage TDRSS to develop a truly on-demand commanding capability, similar to what exists from commercial providers (e.g., GlobalStar or Iridium), the commanding equivalent of the TDRSS Demand Access System (DAS) that already exists and is regularly used by Swift for return service. Such a capacity is also necessary for strong science cases demanding commanding with latency on the order of seconds (Tohuvavohu et al. 2020c, in preparation), as compared to the latency of some minutes described here. Absent such a capability from TDRSS, we remark that it may behoove designers of next-generation extremely rapid-response space telescopes to consider the use of a commercial network for their ToO, or other extremely low-latency commanding.

The development of GUANO for Swift serves as a flight-proven retirement of the risk associated with fully autonomous space telescope commanding, and thus opens the door for such capabilities to be included in the design of future missions. In the upcoming era of high-transient detection rates from the likes of the Vera C. Rubin Observatory (Ivezic et al. 2019), fully autonomous and rapid transient response and follow-up will become more crucial than ever.

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Software: healpy (Zonca et al. 2019), Matplotlib (Hunter 2007), ligo.skymap (Singer 2018), NumPy (van der Walt et al. 2011).

\(^{14}\)https://www.swift.psu.edu/guano
Appendix

A flowchart depicting the entire GUANO system is shown in Figure A1.

Figure A1. A flowchart depicting the entire GUANO system, from receipt of a trigger to sending a command to Swift and its autonomous interactions with external systems such as the Space Network Access System. The entire system runs continuously, and the GUANO queue scheduler fully reevaluates the optimal strategy to ensure data recovery, every 20 seconds, and requests more commanding resources as necessary.
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