Localization of Gamma-ray Bursts in a Balloon-Borne Telescope

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ABSTRACT

Multi-messenger astrophysics combines observations from multiple instruments to study transient astrophysical phenomena, many occurring at seconds-level timescales. To identify and precisely localize these events in the sky, current systems often search through extensive sensor data, requiring resource-intensive computation to achieve results on the timescale of the events themselves. We seek to reduce computational requirements so as to perform real-time event localization with limited computational resources suitable for an orbital platform.

This work studies the performance of a computational pipeline for real-time gamma-ray burst (GRB) detection and localization aboard the Antarctic Demonstrator for the Advanced Particle-astrophysics Telescope (ADAPT), a balloon-borne prototype for a space-based gamma-ray observatory supporting multi-messenger observations. ADAPT observes gamma-ray Compton scattering, then uses the pipeline to combine information from multiple photons to identify a GRB's source direction. In this paper, we identify, model, and measure key uncertainties, then propose instrumentation and computational improvements to reduce them, substantially improving localization accuracy.

CCS CONCEPTS

• **Applied computing → Astronomy**; *Physics*; • **Computer systems organization → Sensors and actuators**.

KEYWORDS

multi-messenger astrophysics, gamma-ray astronomy

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1 INTRODUCTION

Multi-messenger astrophysics [10, 11] combines observations from many modalities (e.g., gravity waves, neutrinos, EM spectra) to study physical phenomena in the cosmos. Because some events of interest, such as binary neutron star mergers, occur on a time scale of seconds, and many observing instruments have a narrow field of view ($< 1^\circ$ is common for optical telescopes), fast, accurate localization of such transient events in the sky is vital to maximize observing time for these events [8]. Currently, gravity-wave and neutrino detectors are used to perform omnidirectional transient event detection. They both rely on pattern-matching searches through an extensive raw data set, which are quite computationally intensive [6, 8, 9], often running on computational clusters or grids [1]. The cost of search increases as the instruments improve in sensitivity [5]. A key driver of this work is that gamma-ray detection can achieve better localization of transient events, in shorter time, using dramatically lower computational power.

The Advanced Particle-astrophysics Telescope (APT) [2] is a concept for a space-based observatory planned to survey the entire sky for gamma-ray sources in the MeV to TeV range. APT's objectives include prompt detection and localization of energetic transient events such as gamma-ray bursts (GRBs) in the far reaches of the universe, followed by communication to other instruments for focused follow-up observations. A technology demonstration mission for APT's detector hardware, the Antarctic Demonstrator for APT (ADAPT), is now in advanced development with the goal of gathering data from a high-altitude balloon flight in late 2025.

ADAPT aims to localize GRBs within one second of light detection to within a few degrees of arc, even for less-bright GRBs (one to a few MeV/cm^2). We seek to capture short-duration GRBs that will benefit most from prompt follow-up with other instruments at other wavelengths. These GRBs emit gamma rays with energies in the low-MeV range, which interact with ADAPT's detector mainly through multiple Compton scattering.

Given that many of the instruments that will be guided by our initial observations have a narrow field of view, controlling our uncertainty about the estimated sky location of a GRB is crucial to improving the scientific benefits of the observation [8]. Understanding the root causes of localization uncertainty and developing strategies to diminish that uncertainty are foci of our current work.

In prior work [7, 12, 14], we developed a suite of algorithms to detect and localize GRBs in real time. These algorithms are designed to run on low-power computing hardware co-located with ADAPT's detector. To validate our methods, we use computational models of the detector hardware [3, 13] and of diffuse background radiation that obscures light from GRBs [4].

This work identifies sources of the uncertainty in localization arising from ADAPT's physical limitations and the presence of background radiation. We show that limitations in measuring the energy deposited by gamma-ray interactions with the detector are the dominant contributor to this uncertainty but can be mitigated by deploying additional detector hardware. We also improve our software pipeline's ability to exclude noise caused by background particles. We quantify the resulting improvements in localization

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accuracy and assess the current localization uncertainty in our system, considering how a GRB's brightness and its the angle of incidence with respect to the detector impact accuracy.

2 BACKGROUND

ADAPT's (and APT's) gamma-ray detector is composed of multiple layers of CsI(Na) crystalline scintillator, which emit light when incoming gamma-ray photons scatter within them. Each layer is lined with optical fibers to capture this light, from which we measure both the exact position of the photon's interaction with the crystal and how much energy it deposited. A photon may scatter multiple times in one or more layers before finally being photoabsorbed; the angle at which the photon scatters at each step is related by the Compton law to the amount of energy it deposits.

We refer to each gamma-ray interaction within a layer as a *hit*, while a collection of hits caused by multiple scatterings from a single gamma ray is termed an *event*. The hits from an event are represented as a list of pairs $(\mathbf{r}_i, E_i)$, where $\mathbf{r}_i$ is a 3-vector indicating the coordinates of the ith interaction, and E_i denotes the energy deposited by the photon during that interaction.

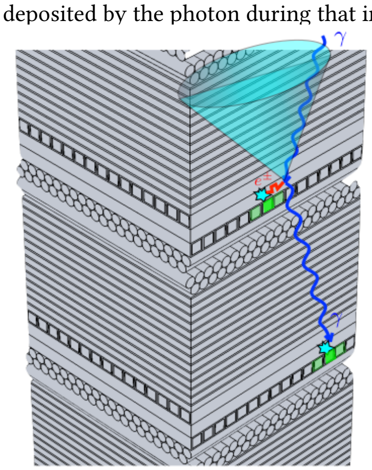


Figure 1: Multiple Compton scattering of a gamma ray [2].

We now provide a brief overview of our computational approach to GRB localization; a comprehensive description is available in [12]. Processing is conducted in two phases. In the first phase, *reconstruction*, we reconstruct the trajectory of each single-gamma-ray event within the detector using its list of hit positions and energies. Due to the short time intervals between hits, they appear simultaneous; hence, we must infer their order by considering multiple possible orderings and selecting one for which the implied energy deposits and scattering angles best agree with the Compton law. Reconstruction reduces the jth gamma-ray photon to a vector $\mathbf{c}_j$ through the coordinates of its first two interactions and an estimate ϕ_j of the angle between the gamma-ray's source direction $\mathbf{s}$ and $\mathbf{c}_j$. The pair $(\mathbf{c}_j, \phi_j)$ defines a *Compton ring* around $\mathbf{c}_j$, as illustrated in Figure 1. The gamma ray's source direction in the sky lies somewhere on this ring.

In the second phase, *localization*, we intersect Compton rings from hundreds or thousands of events to infer a common source direction for the GRB. Due to inaccuracies in the inferred centers and angles of the rings, finding a single common point of intersection is unlikely. Thus, we face a noisy, overdetermined problem. We tackle this challenge by first using a small random sample of Compton rings and a likelihood model to estimate an approximate source direction, then apply iterative least-squares refinement using all available rings to improve the accuracy of the initial estimate.

For the experiments described here, we simulate GRBs with properties similar to previously cataloged short bursts, as detailed in [7, Section 2], using the GEANT4 physics simulator. When measuring our accuracy in localizing a simulated GRB, we perform 1000 trials with gamma-ray photons randomly generated by GEANT4 from the GRB's energy distribution. We report localization accuracy as 68% and 95% *containment* values, where a p% containment value means that p% of trials localized the GRB to within the given angular error (in degrees). Furthermore, each experiment is repeated 10 trials to obtain the 95% interval bars.

3 NOISE AND UNCERTAINTY

Our reconstruction algorithms assume that an event in the instrument corresponds to one or more Compton scatterings in the scintillator layers followed by a final photoabsorption. However, not all interactions follow this simple model. Some photons may scatter out of the instrument without being photoabsorbed, while others may interact in parts of the detector other than the scintillators. In both cases, total detected energy is less than the actual energy of the gamma-ray photon. Moreover, a small proportion of gamma rays undergo *pair production* (a physical process distinct from Compton scattering), and other physical phenomena such as *Bremsstrahlung* may create secondary gamma-ray photons whose direction is unrelated to those from the GRB. Finally, two nearby interactions in a single detector layer may not be separately resolvable. All of these scenarios can result in an incorrectly reconstructed Compton ring that does not pass near the GRB's source direction.

We plan to deploy ADAPT in the Earth's upper atmosphere, where it will be exposed to the anisotropic background radiation of the Earth's limb. These background particles contribute to a diffuse distribution of additional Compton rings that can obscure the signal from a GRB, adding further noise to the localization process.

In addition to the noise from ADAPT's physical environment, we have modeled noise from its electronics as described in [13]. There exist several sources of baseline or background noise in our detector devices (optical fibers, photomultipliers, and A/D converters). Moreover, the light collection efficiency of these devices depends on the position of a scintillation within a layer. Finally, if multiple photons hit the detector nearly simultaneously, it may be impossible to separate out their events, resulting in a combined signal that does not accurately represent either event.

3.1 Uncertainty of Spatial vs. Energy Measurements

The aforementioned sources of noise more substantially impact estimates of a scintillation's energy compared to its spatial position. In other words, for a hit $(\mathbf{r}_i, E_i)$, the value E_i has greater uncertainty than $\mathbf{r}_i$. To quantify this effect, we perform a data swapping experiment where we select the gamma-ray photons for which all interactions are individually and correctly detectable, i.e., each hit matches a corresponding interaction in the simulated ground truth. From these resulting 146 354 "good" events from our corpus of 10^6 gamma-ray photons for one of our normally-incident bursts, we sample a number of photons corresponding to a total event brightness (fluence) of 1 MeV/cm^2. In Figure 2, we compare the localization accuracy when reconstructing based on the ground-truth spatial and/or energy measurements for each photon (obtained from GEANT4) vs. those obtained from ADAPT's noisy fiber readouts. We see that using the ground truth for the spatial estimates decreases localization error only slightly, whereas using ground-truth energy estimates substantially reduces overall error. This result highlights the importance of reducing uncertainty in the instrument's energy measurements.

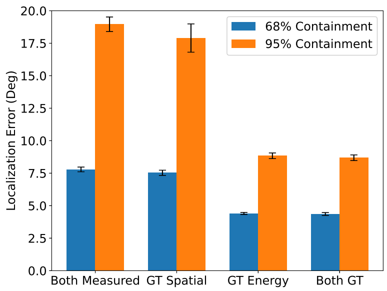


Figure 2: Localization accuracy using ground truth (GT) vs. noisy measured spatial and energy estimates.

3.2 Strategies to Improve Energy Estimates

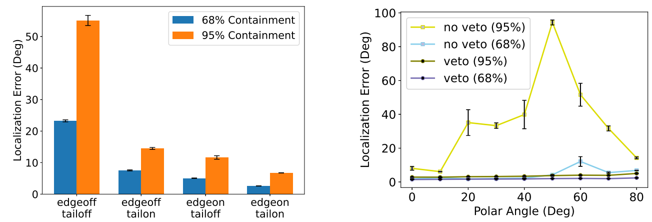
In addition to the optical fibers running across the surfaces of its scintillator layers, we extended ADAPT's design to incorporate *edge detectors* – extra strips of photomultipliers placed over two of the outward-facing edges of each layer to capture additional optical signals. Their optical and electronic properties are detailed in [13]. Depending on the scintillation position, edge detectors capture 3 to 11 times more light from scintillations than the fibers alone. This improved light capture allows better estimation of the energy deposited by each gamma-ray interaction with a layer.

ADAPT also incorporates *tail counters*, which are constructed similarly to the regular detector layers but lack optical fibers. The absence of fibers means that precise spatial positions of interactions with the tail counters are not available, and so these interactions are not included in the list used for reconstruction. However, the additional layers increase the likelihood that an incident photon will be photoabsorbed, and hence that we will correctly measure its total energy.

To quantify the improvement in localization accuracy achieved by edge detectors and tail counters, Figure 3a measures accuracy with and without this additional hardware enabled on the same simulated burst as in Figure 2 but this time, sampled from the full corpus of 10^6 gamma-ray photons. The remaining experiments in this paper employ the full corpus as well. The additional energy gathered by the two hardware features, individually and in combination, substantially reduces energy uncertainty and hence improves localization.

3.3 Atmospheric Particle Background

To address noise introduced by atmospheric background particles, our analytical pipeline implements two strategies to veto background particle events. First, we reject all events where two or more interactions occur in the same layer, as these are more likely to be caused by background particles. This approach effectively removes background-derived Compton-rings that could contaminate the localization phase. Second, we take advantage of the fact that



(a) Effect of edge detectors and tail counters on localization.

(b) Effect of background veto on localization (2 MeV/cm^2).

Figure 3: Localization accuracy improvements.

GRBs detected by ADAPT can only occur above a horizontal plane through the detector. Therefore, our software pipeline rejects all reconstructed events where the Compton ring lies entirely below the horizontal.

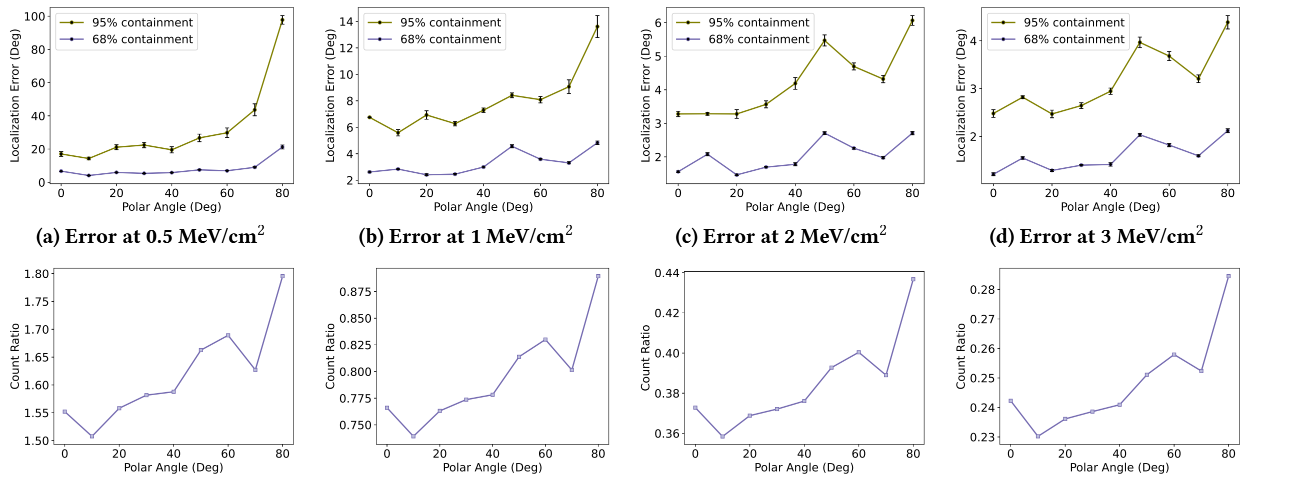
Figure 3 illustrates the impact of our background veto rules on localization accuracy for a simulated GRB of fluence 2 MeV/cm^2. Because background is anisotropic, its impact on accuracy depends on the incident angle of the source GRB relative to the detector. With no background veto, accuracy is catastrophically lost for incident angles between 20 and 70 degrees from normal (i.e., from a vertical line through the detector). Adding the veto to the software pipeline largely recovers this loss, even though it also excludes 10% or more of gamma rays from the burst. Veto is even more important at lower fluences; e.g., at 1 MeV/cm^2, localization is near-impossible at any angle without it (data not shown).

4 LOCALIZATION RESULTS

We now present simulation results that more completely characterize the uncertainty in ADAPT's GRB localization after adding all the improvements described in the previous section. We show results for a range of GRB brightness (fluence 0.5 to 3 MeV/cm^2). We also show how our results change with the GRB's incident angle, to capture any uncompensated impacts of atmospheric background as well as the greater difficulty of reconstructing trajectories for photons that enter the detector from the side (and hence tend to interact with fewer scintillator layers).

Figures 4(a)–(d) illustrate the errors in localization with changing fluence and incident angle. Brighter GRBs produce more incident photons and so provide more data from which to localize. For bursts at low incident angles (close to normal to the detector), ADAPT typically achieves 2-3 degrees of accuracy for fluence 1 MeV/cm^2 and less than one degree for 3 MeV/cm^2. The error broadly increases with increasing angle; moreover, despite the effectiveness of the veto algorithms at removing background events, we see non-monotonic degradation qualitatively similar to that of Figure 3b, though smaller, at 50-60 degrees.

To further elucidate the causes of localization uncertainty, Figures 4(e)–(h) measure the ratio between the number of Compton rings reconstructed from background particles (and hence totally unrelated to the source GRB) that survive the veto process to the number of rings reconstructed from actual GRB photons. This *count ratio* captures the extent to which the background dilutes signals from the GRB in the localization phase of our pipeline. As expected, brighter GRBs contribute more photons and reduce the count ratio. We note that the count ratio is non-monotonic with incident angle, which may reflect angular dependence of background intensity, or



(a) Error at 0.5 MeV/cm^2
(b) Error at 1 MeV/cm^2
(c) Error at 2 MeV/cm^2
(d) Error at 3 MeV/cm^2
(e) Count Ratio (0.5 MeV/cm^2)
(f) Count Ratio (1 MeV/cm^2)
(g) Count Ratio (2 MeV/cm^2)
(h) Count Ratio (3 MeV/cm^2)

Figure 4: Localization accuracies and corresponding count ratios for ADAPT.

variations in effectiveness of the background veto and in our ability to capture and reconstruct source photons. Future work will study the interplay among these factors.

Finally, we note that all localizations shown here were computed in well under one second on a Raspberry Pi 3B+, which roughly approximates the level of computing power we expect to deploy on an eventual orbital platform. Hence, we do achieve our overall goal of prompt localization with limited computational resources.

5 CONCLUSION AND FUTURE WORK

ADAPT and the future APT mission aim to provide prompt, accurate localization of gamma-ray transients in the sky, making them effective partners in multimessenger astrophysics observation. We have shown that uncertainty in the measured energy of incident gamma-ray photons, as well as noise from atmospheric background particles, are serious challenges to ADAPT's performance, and that additions to its detector hardware and software processing pipeline can mitigate these challenges. We further characterized the uncertainty of our improved ADAPT pipeline on simulated GRBs, considering the impact of both brightness (fluence) and incident angle of the GRB to the detector. Overall, ADAPT is expected to achieve typical localization accuracy of 2-3 degrees for moderately bright short-duration GRBs.

Future work will focus on extending our results to the full orbital APT instrument, for which its greater size and lack of atmospheric background should permit sub-degree localization accuracy. We will also consider additional sources of potential uncertainty, in particular limitations on the bandwidth of the detector's electronics that could reduce the effective number of incident photons available for use in localization.

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