Promt and Accurate GRB Source Localization Aboard the Advanced Particle Astrophysics Telescope (APT) and its Antarctic Demonstrator (ADAPT)

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1. Overview

The Advanced Particle-astrophysics Telescope (APT) [1,3] is a mission concept aimed at prompt localization of MeV transients such as GRBs, with all-sky sensitivity and a large effective area. ADAPT (the Antarctic Demonstrator for APT), a scaled-down version of the instrument, is under construction and scheduled to fly from Antarctica in late 2025. Whereas APT has 20 imaging CsI calorimeter (ICC) layers, each a square m on a side, ADAPT has only 4 ICC layers, each 450 cm on a side. The prompt (~1s) reconstruction and integration of evidence from multiple Compton scatters raises significant computational challenges. In this work, we describe improvements made to our GRB localization pipeline and its characterization since ICRC 2021 [2]. Our methodological improvements enhance both localization accuracy and computation efficiency, while new optical and electronics models of APT and ADAPT [5] provide more realistic accuracy estimates and illustrate the importance of ADAPT’s SiPM-based edge detectors and tail counters. For additional realism, we have incorporated the atmospheric background model for ADAPT from [6] and devised methods to reject background particles. Despite challenges of instrument noise and background, we expect prompt, accurate GRB localization from ADAPT and sub-degree localization accuracy from full APT for GRB fluxes as low as 0.1 MeV/cm².

2. Background

How We Localize GRBs

Gamma-ray photons from a GRB enter the instrument, interacting via Compton-scattering one or more times before being photoabsorbed. As described in [2], GRB localization occurs in two phases:

1. Reconstruction
   - Infers time ordering of one photon’s interactions w/detector
   - Uses accelerated Boggs-Jean algorithm [7]
   - Photon reduces to Compton ring (c, φ), where c is vector through first two interactions and φ is inangle between c and photon’s source direction

2. Localization
   - Intersects 100s to 1000s of photons’ Compton rings to infer common source direction s
   - 1. Produce rough guess at s by testing likelihood of candidate directions from small random sample of Compton rings
   - 2. Use iterative least-squares to refine estimate of s until convergence

GRB Model

- Simulated bursts with Band spectra [8]; α=0.5, Fpeak = 490 keV, β ∈ [-3.2,-2.1]
- Spectral energies in [10 kHz-30 MeV] to match sensitivity of Fermi GBM [9]
- Burst duration of one second, with time-intensity profile of [S, Sec. 5] ...

Measuring GRB Localization Accuracy

- Infer source direction from GEANT4-simulated photons from model burst(s)
- Measure angular diff. between true, inferred source directions
- Over 1000 trials, report 68%, 95% containment values (i.e., 68%/95% of trials yield at most given angular error)

3. Improvements to Computational Pipeline

Z-coordinate Estimation

- Compute Z-coordinate estimate using relative widths (i.e., spans of adjacent hit fibers) of signals observed in a layer’s top and bottom fiber arrays

Revised Localization

- Use cosine of scattering angle, η, directly in approximation and refinement of source direction from Compton rings
- Improves localization accuracy and removes expensive arccos calculations

Validation of Improvements

- Tested with simulated burst from our prior work [2], with parameters α = 0.6, β = -2.5 and incident energies from 300 keV to 10 MeV with peak at 1 MeV
- Using device model from prior work, our changes substantially improved accuracy

4. ADAPT-Specific Instrument Improvements and Challenges

ADAPT’s smaller effective area, fewer ICC layers, and exposure to atmospheric background radiations are offset by additional detector hardware (not in APT) that improves its calorimetry.

Edge Detectors (SiPM-based)

- Capture 3-11 times as much light as WLS fibers
- Improve estimate of energy deposited by each gamma-ray interaction with Csl layers

Tail Counters

- 4 extra CsI layers w/o WLS fibers
- Increases chance of photo-absorption
- More likely to capture total energy of gamma-ray photon

Atmospheric Particle Background

ADAPT is exposed to anisotropic background radiation from Earth’s limb, which adds noise that complicates analysis of light from GRBs. To combat this noise, we (1) reject all events in which two or more interactions occur in same layer (2) reject all Compton rings lying entirely below the horizontal, as ADAPT sees only GRBs occurring above horizontal plane

Validation

<table>
<thead>
<tr>
<th>Fluence (MeV/cm²)</th>
<th>Without Rejection</th>
<th>With Rejection</th>
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</thead>
<tbody>
<tr>
<td>0.5</td>
<td>90.00 ± 0.01</td>
<td>91.56 ± 0.05</td>
</tr>
<tr>
<td>1</td>
<td>89.67 ± 0.02</td>
<td>91.46 ± 0.05</td>
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<tr>
<td>2</td>
<td>1.91 ± 0.00</td>
<td>9.03 ± 1.75</td>
</tr>
<tr>
<td></td>
<td>1.54 ± 0.03</td>
<td>3.35 ± 0.11</td>
</tr>
</tbody>
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- Without rejection strategies, severe localization error at lower fluxes
- Rejection mitigates error at both lower and higher fluxes

5. Scaling ADAPT to APT

- We built a simplified model of APT with edge detectors
- Modeled electronics as in [5], greater light attenuation of APT’s longer WLS fibers
- Lacking ADAPT’s detailed optical simulations of Csl layers, we assumed uniform, position-independent light yield at edget detectors
- Observed ~3x improvement in 68% localization accuracy for normally incident 0.1 MeV/cm² bursts
- We recommend future consideration of adding edge detectors to APT

6. Localization Accuracy and Speed

Accuracy

- Tested performance at three incident polar angles per burst (0°, 30°, 60°)
- Reported value average results for azimuth angles 0° and 45°
- For ADAPT, at 1 MeV/cm², accuracy within 2-3° 68% of the time for bursts within the horizon; at 60° from normal, 68% containment within 5°
- For full APT, sub-degree localization accuracy at fluxes > 0.1 MeV/cm²; around 1° at fluence 0.03 MeV/cm²

Timing

- Tested on Raspberry Pi 3B+ (low-power embedded platform)
- Measured time to run GRB analysis pipeline on our model bursts for 200 trials
- Both ADAPT (~207 ms) and full APT (~446 ms) can localize typical short GRBs in well under a second (~ 600 ms worst-case)

References