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

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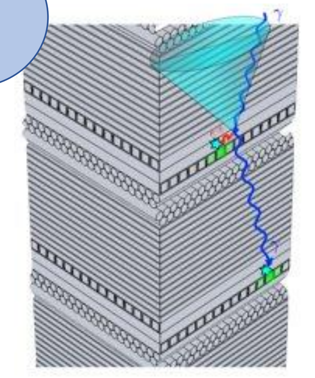
1 Overview

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 3 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 fluences as low as 0.1 MeV/cm^2.

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 inferred angle between **c** and photon's source direction **s**

(2) Localization

- Intersects 100s to 1000s of photons' Compton rings to infer common source direction **s** for GRB
  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, E_{peak}= 490 keV, β ∈ {-3.2,-2.1}
- Spectral energies in [10 keV-30 MeV] to match sensitivity of Fermi GBM [9]
- Burst duration of one second, with time-intensity profile of [5, Sec. 5]
- Generated gamma rays, modeled interactions with detector using GEANT4 [4]

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 lit 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

References

[1] J. Buckley et al., The Advanced Particle-astrophysics Telescope (APT) Project Status, in Proc. of 37th International Cosmic Ray Conference, vol. 395, pp. 655:1–655:9, July 2021, DOI.

[2] M. Sudvarg et al., A Fast GRB Source Localization Pipeline for the Advanced Particle-astrophysics Telescope, in Proc. of 37th International Cosmic Ray Conference, vol. 395, pp. 588:1–588:9, July 2021, DOI.

[3] W. Chen et al., The Advanced Particle-astrophysics Telescope: Simulation of the Instrument Performance for Gamma-Ray Detection, in Proc. of 37th Int'l Cosmic Ray Conference, vol. 395, pp. 590:1–590:9, 2021, DOI.

[4] S. Agostinelli, J. Allison, K. Amako et al., Geant4 — a simulation toolkit, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 506 (2003) 250.

[5] M. Sudvarg et al., Front-End Computational Modeling and Design for the Antarctic Demonstrator for the Advanced Particle-astrophysics Telescope. Poster PGA1-09 (physical).

[6] W. Chen, J. Buckley et al., Simulation of the instrument performance of the Antarctic Demonstrator for the Advanced Particle-astrophysics Telescope in the presence of the MeV background. Poster PGA0-22 (online).

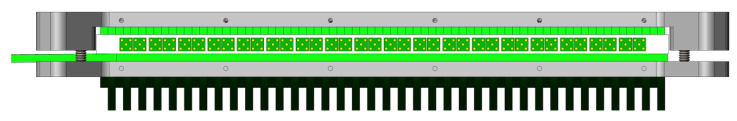
[7] S. Boggs and P. Jean, Event reconstruction in high resolution Compton telescopes, Astronomy and Astrophysics Supplement Series 145 (2000) 311.

[8] D. Band et al., BATSE observations of gamma-ray burst spectra. I. spectral diversity, Astrophys. J. 413 (1993) 281.

[9] "Overview of the Fermi GBM." https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Introduction/GBM_overview.html, Jan. 2020.

4 ADAPT-Specific Instrument Improvements and Challenges

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



Edge Detectors (SiPM-based)

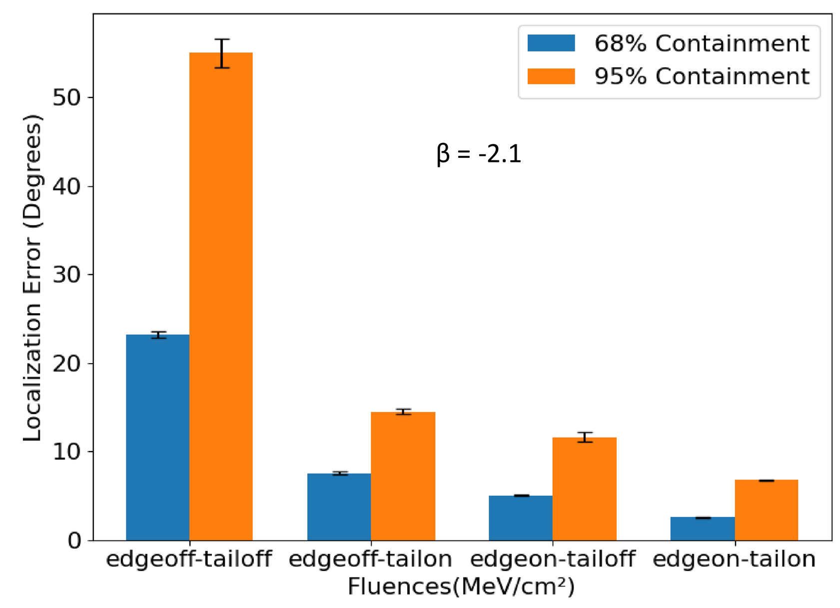
- Capture *3-11* times as much light as WLS fibers
- Improve estimation of energy deposited by each gamma-ray interaction with CsI layers

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

Better Calorimetry Improves ADAPT's Accuracy

Test: Localize two model GRBs assuming normal incidence to detector, fluence of 1 MeV/cm^2



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

Fluence (MeV/cm^2)	Without Rejection		With Rejection	
	68% cnt.	95% cnt.	68% cnt.	95% cnt.
0.5	90.03 ± 0.01	91.56 ± 0.05	6.63 ± 0.02	16.33 ± 1.15
1	89.87 ± 0.02	91.46 ± 0.05	2.58 ± 0.04	6.74 ± 0.04
2	1.94 ± 0.05	9.03 ± 1.75	1.54 ± 0.03	3.15 ± 0.11

- Without rejection strategies, severe localization error at lower fluences
- Rejection mitigates error at both lower and higher fluences

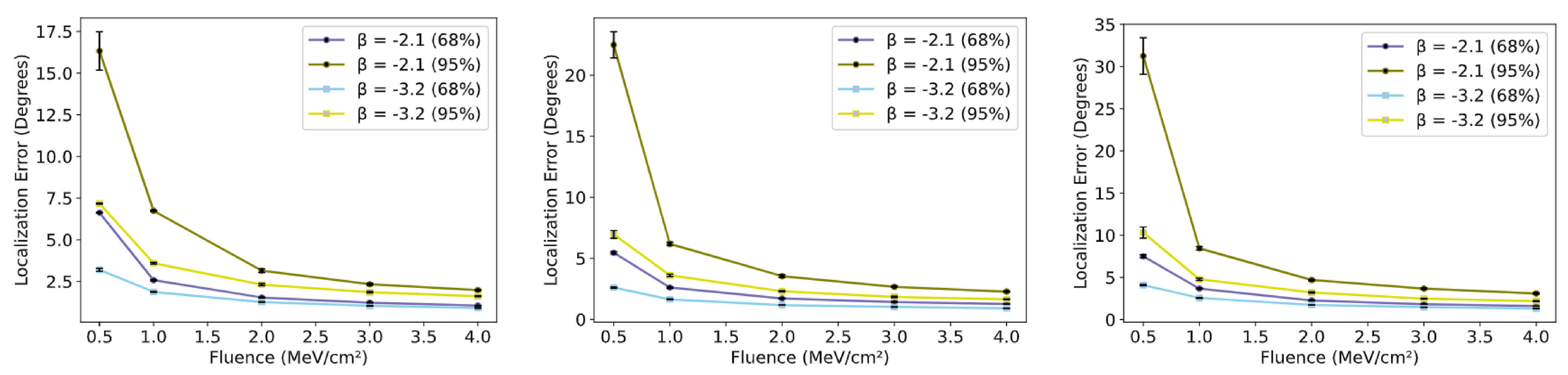
5 Scaling ADAPT to APT

- 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 CsI layers, we assumed uniform, position-independent light yield at edge detectors
- Observed ~3× improvement in 68% localization accuracy for normally incident 0.1 MeV/cm^2 bursts
- ***We recommend future consideration of adding edge detectors to APT***

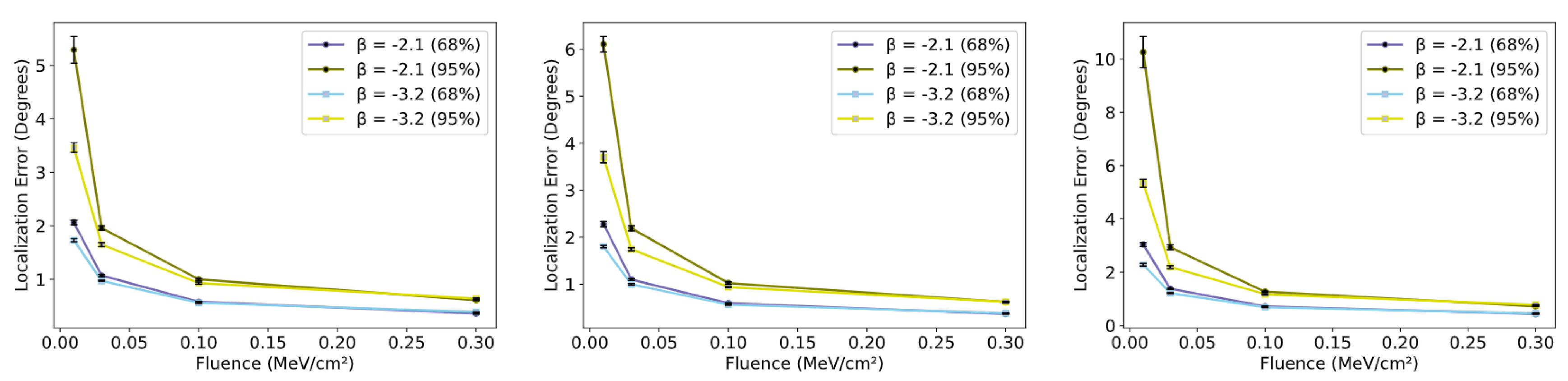
6 Localization Accuracy and Speed

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/cm^2, accuracy within **2-3**° 68% of the time for bursts well above the horizon; at 60° from normal, 68% containment within **5**°
- For full ***APT***, sub-degree localization accuracy at fluences ≥ 0.1 MeV/cm^2; around **1**° at fluence 0.03 MeV/cm^2



(a) ADAPT: 0° polar angle (b) ADAPT: 30° polar angle (c) ADAPT: 60° polar angle



(d) APT: 0° polar angle (e) APT: 30° polar angle (f) APT: 60° polar angle

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)