Performance Modeling and Improvements on the GRB Source Localization Streaming Pipeline Aboard the Antarctic Demonstrator for the Advanced Particle-Astrophysics Telescope (ADAPT)

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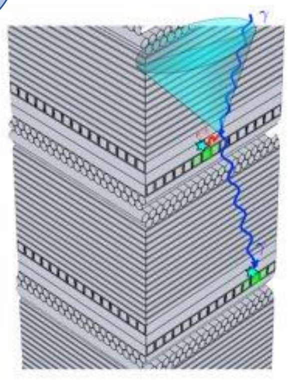
1 Overview

The Advanced Particle-astrophysics Telescope (APT) [1-5] is a mission concept aimed at prompt localization of MeV transients such as GRBs, with all-sky sensitivity and a large effective area. The Antarctic Demonstrator for APT (ADAPT), a small-scale technology demonstration mission for APT's hardware design and computational capabilities, is anticipated to launch using a high-altitude balloon in late 2026 [4, 7-10]. To produce real-time alerts that will direct other, fast-slewing telescopes toward optical counterparts of short-duration GRBs, we implement the computation as a streaming pipeline of concurrently running compute kernels that process a stream of gamma-ray photons over time.

To understand the performance of this design, we model the performance of its two main compute kernels --reconstruction and localization. Using this performance model, we calculate the pipeline's latency and accuracy when producing approximate localization results after seeing only part of the GRB's stream of photons. We show that exploiting such intermediate results would allow a fast-slewing optical telescope to more quickly move to the location of a GRB.

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 [3], GRB localization occurs in two phases:

(1) Reconstruction

- Infers time ordering of *one* photon's interactions w/detector
- Uses accelerated Boggs-Jean algorithm [19]
- 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

(3) Machine Learning

- To address background noise and uncertainty estimation
- Background Network: Classify a Compton ring as originating from either GRB or background
- dEta Network: Estimate uncertainty in angle ϕ of for surviving Compton rings

GRB Model

- Simulated burst with Band spectrum [20]; α=-0.5, E_{peak}= 490 keV, β ∈ -2.35
- Spectral energies in [30 keV-30 MeV] to match sensitivity of Fermi GBM [6]
- Burst duration of one second, with time-intensity profile of [9, Sec. 5]
- Generated gamma rays, modeled interactions with detector using GEANT4 [21]

Measuring GRB Localization Accuracy

- Infer source direction from GEANT4-simulated photons from model burst
- Measure angular diff. between true, inferred source directions

3 Performance Model

Modeling

- Assume T = 1-second burst

$$n_{loc} = \left\lfloor \frac{1 - t_{rec}(E)}{t_{loc}(m, R)} \right\rfloor$$

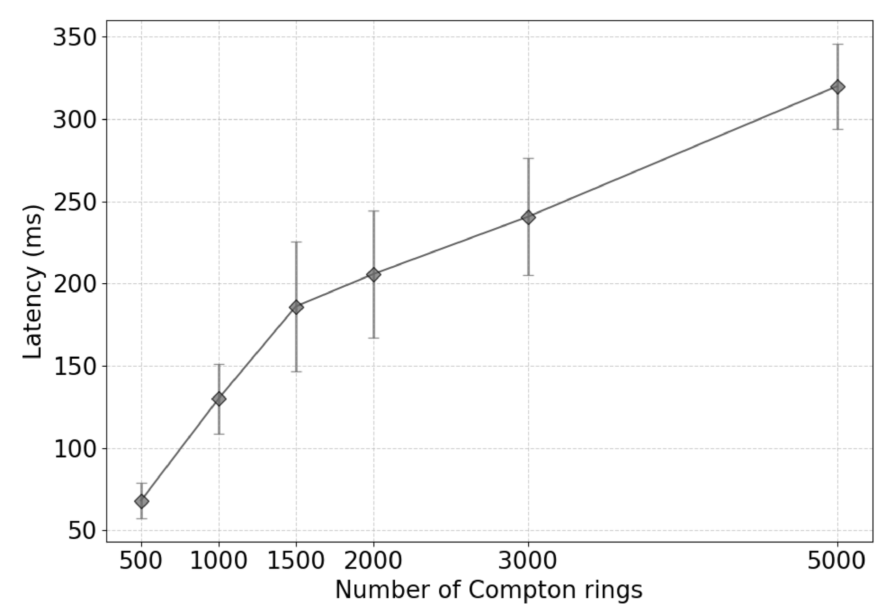
$$w_{min} = \frac{1}{n_{loc}}$$

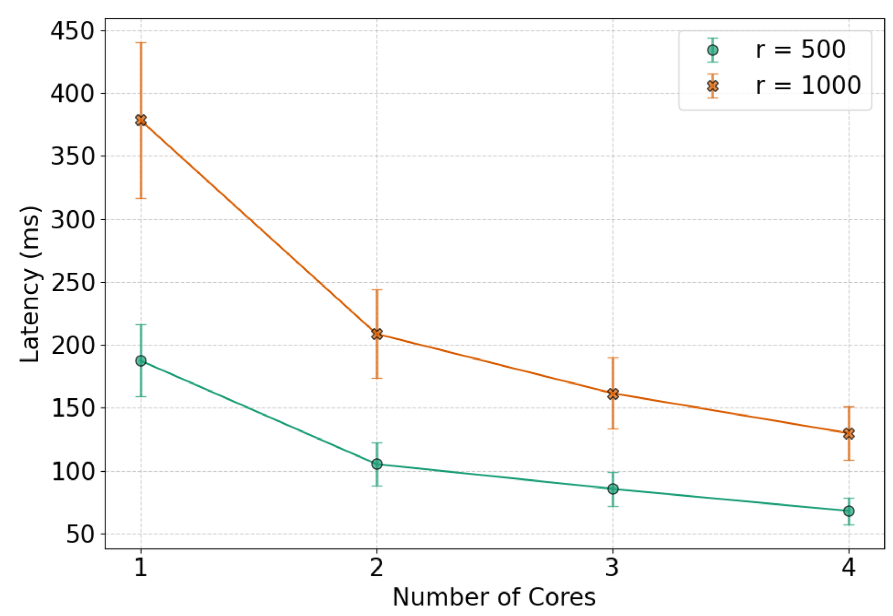
- $t_{rec}(E)$ is execution time of reconstruction kernel on E events using 1 core
- $t_{loc}(m, R)$ is execution time of localization kernel on R Compton rings using m cores
- n_{loc} computes maximum number of localizations possible during a GRB of length T
- w_{min} is minimum possible time interval between alerts

4 Performance Measurements

Experimental Setup

- The pipeline runs on ADAPT's onboard flight instrument computer, a quad-core, 1.92 GHz Intel Atom E3845 CPU.
- Sample both background (from the atmosphere) and source rings
- Varied number of cores and number of Compton rings for localization for 300 trials





- $t_{loc}(m = 4, R)$
- Latency increases more slowly with more rings

- $t_{loc}(m, R \in \{500, 1000\})$
- Significant speedup from 1 core to 4 cores

$$t_{rec}(31{,}746) < 140\ ms;\ t_{loc}(4{,}582) < 100\ ms$$

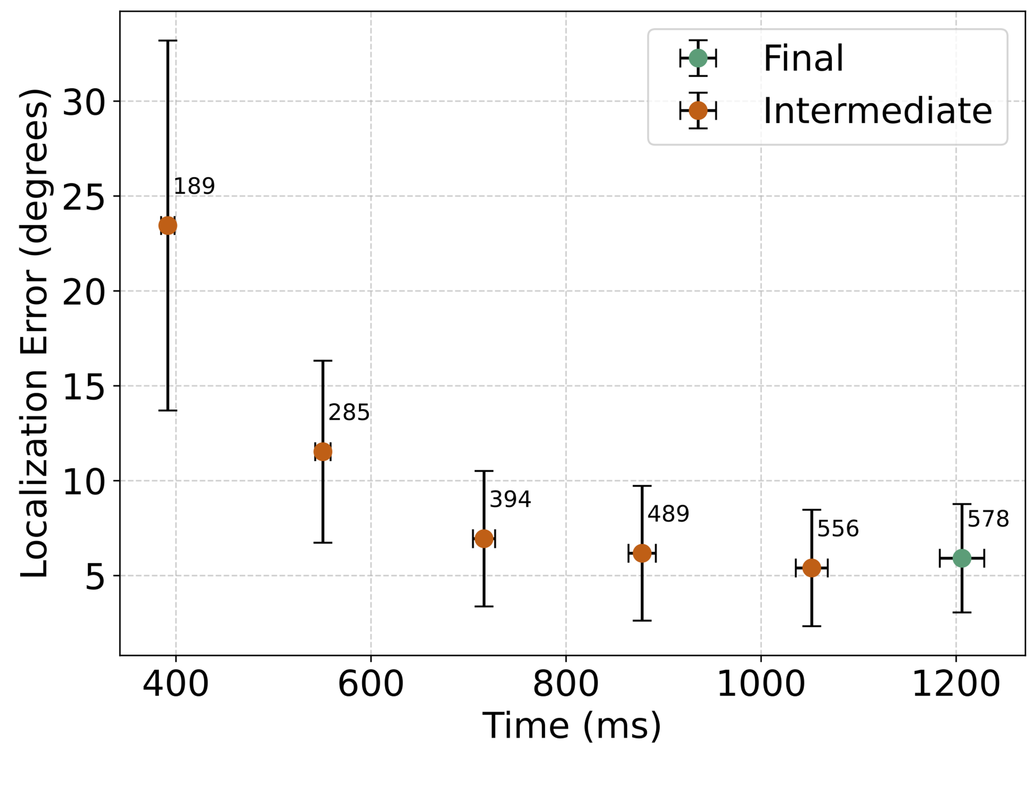
$$n_{loc} = \left\lfloor \frac{1 - 0.14}{0.1} \right\rfloor = 8\ batches,\ w_{min} = \frac{1}{8} = 0.125s = 125\ ms \text{ (set to 150 } ms\text{)}$$

5 Progressive Localization

Compared progressive alerting strategy to a single-alert baseline. Progressive strategy launches localization and produces alert every 150 ms after initial 200 ms delay. Baseline waits until end of GRB to send one final alert.

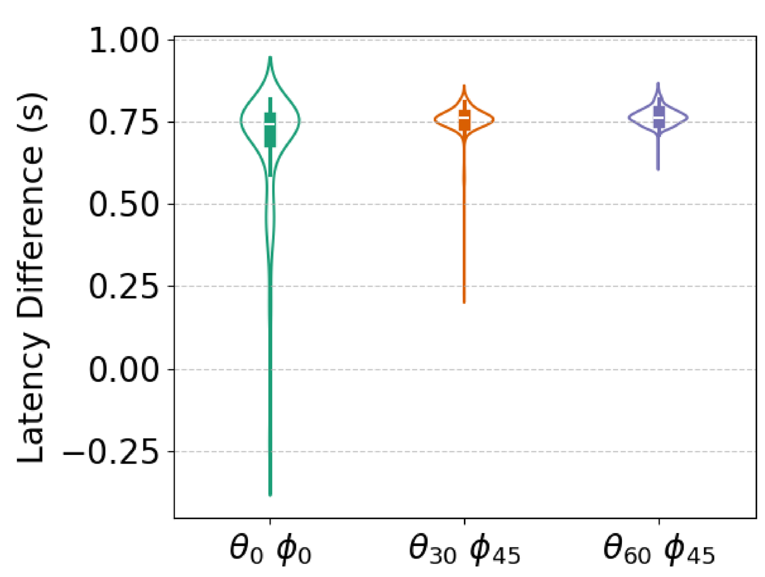
Running Time

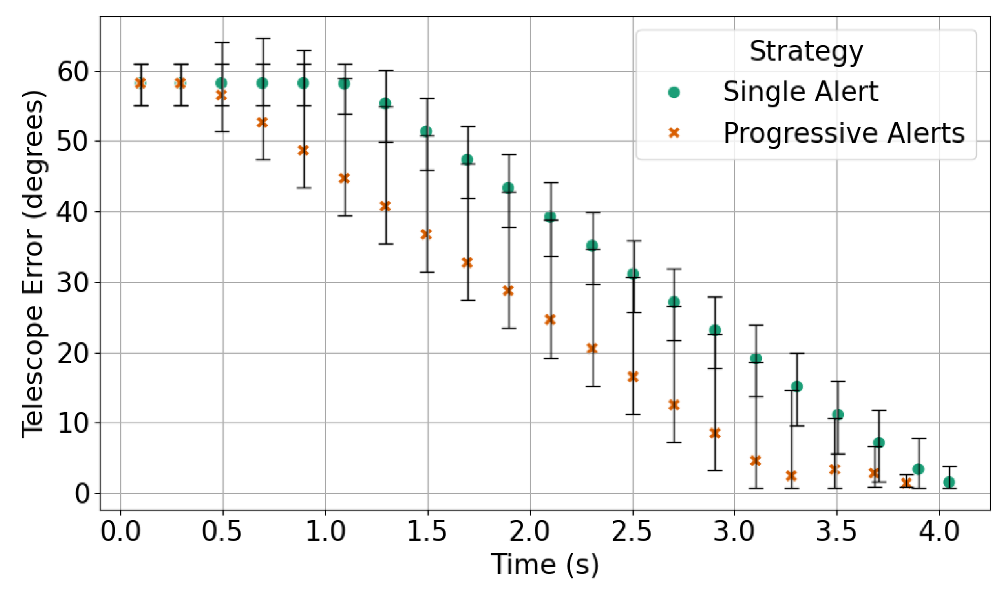
- Computing Intermediate results has little impact on time to deliver final result (1.15s vs 1.21s)
- Plenty of time for reconstruction
- First localization delivered in slightly under 400 ms
- Accuracy significantly improves with each localizations



Utility in Cooperative Pointing

- Assume a partner telescope can slew at 20°/sec and always moves toward most recent localization as soon as it is computed
- Does it reach the final localized position faster (Progressive vs Baseline)?
- Fixed azimuthal angle (45°), varied polar angle (0°, 30°, 60°)





- [Left:] Partner instrument reached target about 0.75 s (19%) faster with progressive strategy than with baseline strategy
- [Right:] Exploiting intermediate localizations begins to reduce median telescope error (with min/max error bars) at around 500 ms after triggering

6 Conclusion

- We show the feasibility of producing progressive alerts as the GRB occurs, which can be used to guide observing partners in real time
- Can produce useful alerts every 150 ms, with increasing accuracy, after first 200 ms for 1 MeV/cm² burst
- Telescope simulation with 20°/sec slew rate suggests about 0.75 s earlier on-target time using progressive alerts compared to single alert

[1] W. Chen et al., The Advanced Particle-astrophysics Telescope: simulation of the instrument performance for gamma-ray detection, in Proc. 37th Int'l Cosmic Ray Conf., vol. 395, pp. 590:1–590:9, 2021, DOI.
[2] J. Buckley et al., The Advanced Particle-astrophysics Telescope (APT) project status, in Proc. 37th Int'l Cosmic Ray Conf., vol. 395, pp. 655:1–655:9, July, 2021, DOI.
[3] M. Sudvarg et al., A fast GRB source localization pipeline for the Advanced Particle-astrophysics Telescope, in Proc. of 37th Int'l Cosmic Ray Conf., vol. 395, pp. 588:1–588:9, July, 2021, DOI.
[4] Y. Htet et al., Prompt and accurate GRB source localization aboard the Advanced Particle Astrophysics Telescope (APT) and its Antarctic Demonstrator (ADAPT), in Proc. 38th Int'l Cosmic Ray Conf., vol. 444, pp. 956:1–956:9, July, 2023, DOI.
[5] J.H. Buckley, J.D. Buhler and R.D. Chamberlain, The Advanced Particle-astrophysics Telescope (APT): computation in space, in Proc. 21st ACM Int'l Conf. Computing Frontiers Workshops and Special Sessions, pp. 122–127, May, 2024, DOI.
[6] C. Meegan, G. Lichti, P.N. Bhat et al., The Fermi gamma-ray burst monitor, Astrophysical J. 702 (2009) 791.
[7] J.D. Meyers, Curator, "Overview of the Fermi GBM." https://fermi.gsfc.nasa.gov/ssc/data/analysis/ documentation/Cicerone/Cicerone_Introduction/GBM_overview.html, Jan., 2020.
[8] W. Chen et al., Simulation of the instrument performance of the Antarctic Demonstrator for the Advanced Particle-astrophysics Telescope in the presence of the MeV background, in Proc. 38th Int'l Cosmic Ray Conf., vol. 444, pp. 841:1–841:9, July, 2023, DOI.
[9] M. Sudvarg et al., Front-end computational modeling and design for the Antarctic Demonstrator for the Advanced Particle-astrophysics Telescope, in Proc. 38th Int'l Cosmic Ray Conf., vol. 444, pp. 764:1–764:9, July, 2023, DOI.
[10] M. Sudvarg, C. Zhao, Y. Htet, M. Konst et al., Hls taking flight: Toward using high-level synthesis techniques in a space-borne instrument, in Proc. 21st ACM Int'l Conf. Computing Frontiers, pp. 115–125, 2024.
[11] Y. Htet, M. Sudvarg, J.D. Buhler, R.D. Chamberlain and J.H. Buckley, Localization of gamma-ray bursts in a balloon-borne telescope, in Proc. Wkshps. Int'l Conf. High Performance Computing, Network, Storage, and Analysis (SC-W), pp. 395–398, Nov., 2023, DOI.
[12] M. Sudvarg et al., FPGA-Based Data Processing using High-Level Synthesis on the Antarctic Demonstrator for the Advanced Particle-astrophysics Telescope (ADAPT), in Proc. 39th Int'l Cosmic Ray Conf., vol. 501, pp. 852:1–852:9, July, 2025.
[13] S.E. Boggs and P. Jean, Event reconstruction in high resolution Compton telescopes, Astronomy and Astrophysics Suppl. Series 145 (2000) 311.
[14] M. Sudvarg et al., Parameterized workload adaptation for fork-join tasks with dynamic workloads and deadlines, in Proc. of 29th Int'l Conf. on Embedded and Real-Time Computing Systems and Applications (RTCSA), 2023, DOI.
[15] Y. Htet, M. Sudvarg, D. Butzel, J.D. Buhler, R.D. Chamberlain and J.H. Buckley, Machine learning aboard the ADAPT gamma-ray telescope, in Proc. of Workshops of the International Conference on High Performance Computing, Network, Storage, and Analysis (SC-W), pp. 4–10, Nov., 2024, DOI.
[16] J.H. Kim, M. Im, H. Lee, S.-W. Chang, H. Choi and G.S.H. Paek, Introduction to the 7-Dimensional Telescope: commissioning procedures and data characteristics, in Ground-based and Airborne Telescopes X, H.K. Marshall, J. Spyromilio and T. Usuda, eds., vol. 13094, p. 130940X, International Society for Optics and Photonics, SPIE, 2024, DOI.
[17] D. Wang, Y. Htet, M. Sudvarg, R. Chamberlain, J. Buhler and J. Buckley, Coordinating instruments for multi-messenger astrophysics, in Proc. of 22nd ACM International Conference on Computing Frontiers Workshops and Special Sessions, pp. 213–218, May, 2025, DOI.
[18] J. Buhler and M. Sudvarg, Real-time Likelihood Map Generation to Localize Short-duration Gamma-ray Transients, in Proc. 39th Int'l Cosmic Ray Conf., vol. 501, pp. 587:1–587:9, July, 2025.
[19] S.E. Boggs and P. Jean, Event reconstruction in high resolution Compton telescopes, Astronomy and Astrophysics Suppl. Series 145 (2000) 311.
[20] D. Band et al., BATSE observations of gamma-ray burst spectra. I. spectral diversity, Astrophys. J. 413 (1993) 281.
[21] 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.