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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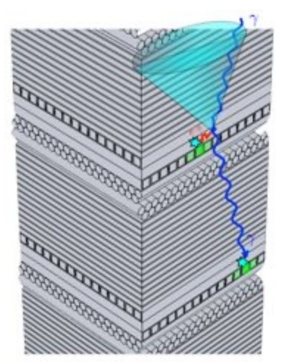
1 Overview

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, 6-9]. 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 model, we calculate the pipeline's latency and accuracy when producing approximate localization results after observing only part of the GRB's stream of photons. We show that exploiting such intermediate results would allow a fast-slewing optical telescope to move to the location of a GRB more quickly.

In this work, my major contribution is to run and test the performance of the pipeline under different setups, including reconstruction, localization, and stream pipeline, to confirm that the data and graphs in the paper can correctly and accurately represent how the stream pipeline behaves. Also, I am doing some debugging on Reconstruction to prepare for the August paper publication.

2 Background



How We Localize GRBs

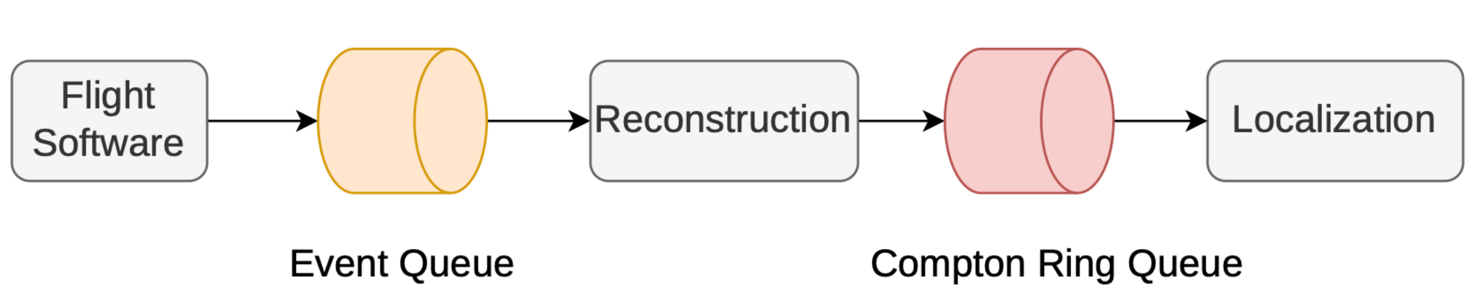
Gamma-ray photons from a GRB enter the instrument, interacting via Compton-scattering one or more times before being photoabsorbed. As described in [3], GRB localization occurs in two phases:

(1) Reconstruction

- Infers time ordering of *one* photon's interactions w/detector
- Uses accelerated Boggs-Jean algorithm [10]
- Photon reduces to *Compton ring* ($\mathbf{c}$, ϕ), where $\mathbf{c}$ is vector through first two interactions and ϕ is inferred angle between $\mathbf{c}$ and photon's source direction $\mathbf{s}$

(2) Localization

- Intersects 100s to 1000s of photons' Compton rings to infer common source direction $\mathbf{s}$ for GRB
  1. Produce rough guess at $\mathbf{s}$ by testing likelihood of candidate directions from small random sample of Compton rings
  2. Use iterative least-squares to refine estimate of $\mathbf{s}$ until convergence
- Machine Learning Methods used in the kernel
  1. To address background noise and uncertainty estimation
  2. Background Network: Classify a Compton ring as originating from either GRB or background
  3. dEta Network: Estimate uncertainty in angle ϕ of for surviving Compton rings



3 Performance Model

Modeling

Assume T = 1-second burst

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

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

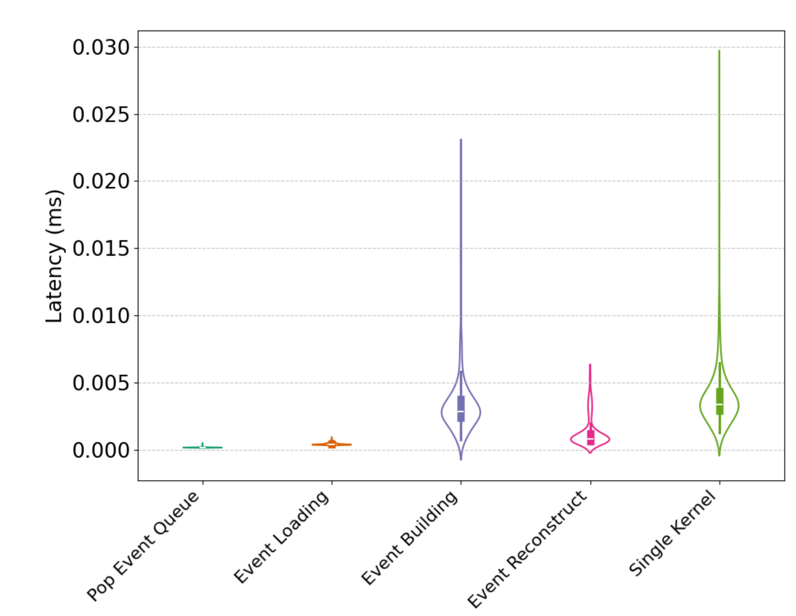
- $t_{rec}\,(n, E)$ is execution time of reconstruction kernel on E Gamma-ray events using n cores
- $t_{loc}\,(m, R)$ is execution time of localization kernel on R Compton rings using m cores
- n_{loc} computes maximum number of localizations possible during a GRB of length T
- w_{min} is minimum possible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

To get the parameters of this model, we need to conduct several experimental runs with the setup below:

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, number of Gamma-ray events for reconstruction, and number of Compton rings for localization for 300 trials

4 Reconstruction Measurements

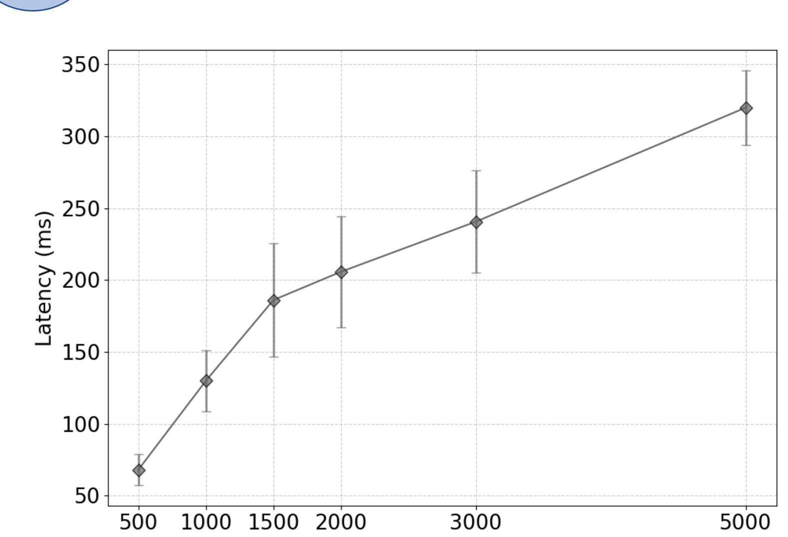


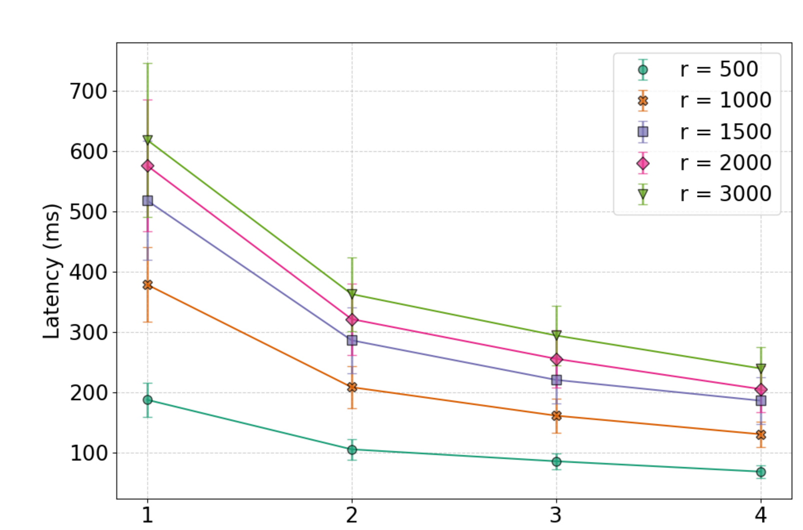
- $t_{rec}\,(n = 1, E = 31{,}746) < 140\ ms$
- Desirable execution time in single thread setting
- Sufficiently fast for follow-up stage like localization

- clock_gettime(steady_clock) version of timing
- Small overhead compared to other benchmark libraries
- Suitable for rapid, frequent timing

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

5 Localization Measurements



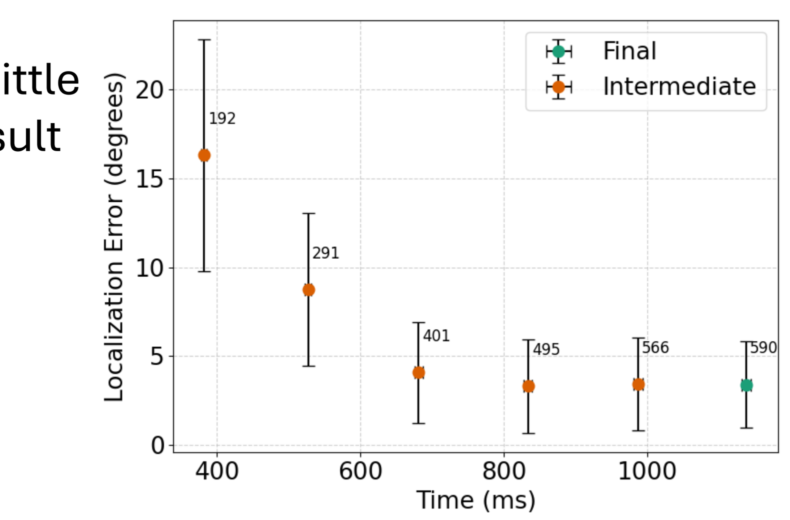


- $t_{loc}\,(m = 4, R = 582) < 100\ ms$
- Latency increases more slowly with more rings

- $t_{loc}\,(m, R\ \in\ \{500, 3000\})$
- Significant speedup from 1 core to 4 cores

6 Pipeline Measurements

Running Time

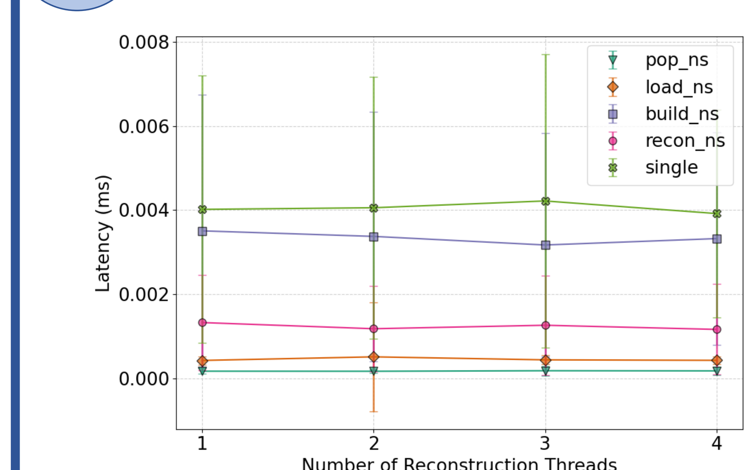


- Computing Intermediate results has little impact on time to deliver the final result (1.15s vs. 1.21s)
- Plenty of time for reconstruction
- First localization delivered in slightly under 400 ms
- Accuracy significantly improves with every new localization launch

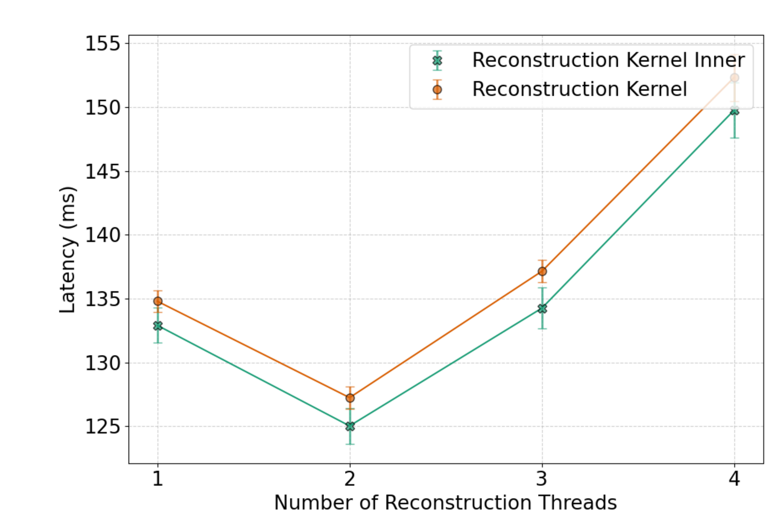
For more information, please visit our website archive:
SBS Lab: *https://sbs.wustl.edu/publications.shtml*
ICRC Paper: *https://sbs.wustl.edu/pubs/ICRC2025_679.pdf*

7 Future Work

Reconstruction Optimization

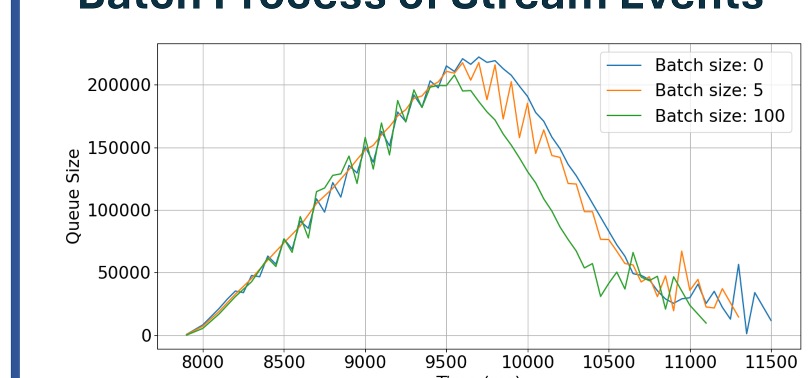


- For each single stage in reconstruction, the latencies are stable for different numbers of threads
- We expect better performance overall using more threads for reconstruction

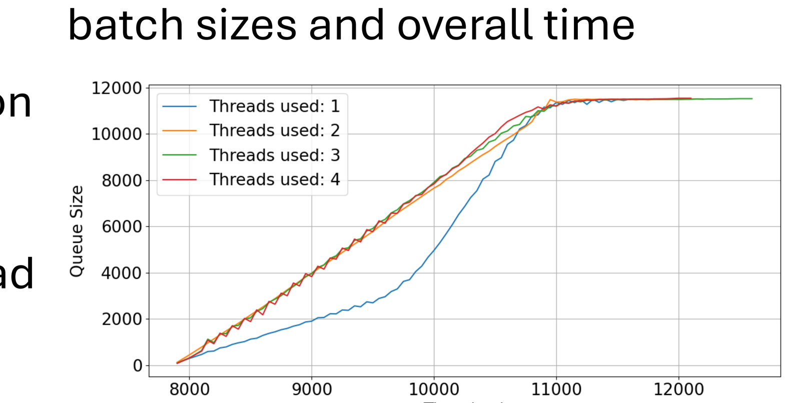


- Answer the question of why an increasing number of cores for Reconstruction does not improve the runtime
- Figure out where does this discrepancy come from

Batch Process of Stream Events



- Faster consumption of Gamma-ray Events inside the event queue using batch processing
- Smaller locking overhead compared to popping one at a time
- Need more experiments on different batch sizes and overall time



- Multiple threads produce Compton rings faster and steadier
- More information regarding each localization launch than one thread
- No significant difference between two, three, and four threads

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