Neural Network Extensions for the GRB Localization Pipeline on the ADAPT Gamma-Ray Telescope

Ye Htet (htet.ye@wustl.edu), Marion Sudvarg, Jeremy Buhler, Roger Chamberlain, James Buckley for the APT collaboration

Funded by NASA award 80NSSC21K1741

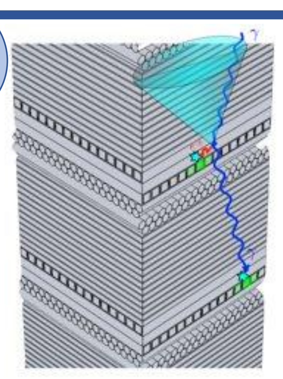
https://adapt.physics.wustl.edu/

1 Overview

The Advanced Particle-astrophysics Telescope (APT) [1,3] is a space-based mission concept that will offer all-sky coverage and rapid localization of MeV transients like gamma-ray bursts (GRBs). Its high-altitude balloon prototype, ADAPT, is under construction and anticipated to fly from Antarctica in late 2026. A significant challenge for both APT and ADAPT is the strict size, weight, and power constraints imposed on their computing platforms, together with the requirement to quickly reconstruct and integrate evidence from multiple Compton scatters of incoming photons. To localize a burst, the instrument reconstructs the Compton ring described by each photon's initial scatter. The intersection of these rings then reveal's the GRB's common source direction. We are developing a computational pipeline that can perform this reconstruction and localization rapidly and accurately to enable follow-up observations of even sub-second bursts by narrow field-of-view instruments.

This poster describes our recent work to integrate two neural networks into ADAPT's computational pipeline to mitigate the effects of noise from the atmospheric background radiation and enhance localization accuracy. One network is designed to remove background radiation signals, while the other estimates the uncertainty in the diameter of each reconstructed Compton ring. Validating the accuracy and computational efficiency of these networks through simulations of GRB detection for the ADAPT prototype, we find that ADAPT will be able to localize short GRBs with fluence at least 1 MeV/cm^2 to within 6° of error at least 68% of the time in under 1 second.

2 Background



How We Localize GRBs

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

(1) Reconstruction [2, 7]

- Infers time ordering of *one* photon's interactions w/ detector
- Photon reduces to *Compton ring* (**c**, ϕ), where **c** is vector through first two interactions and ϕ (also η = cos ϕ) is inferred angle between **c** and photon's source direction **s**

(2) Localization [2]

- Intersects 100s to 1000s of 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

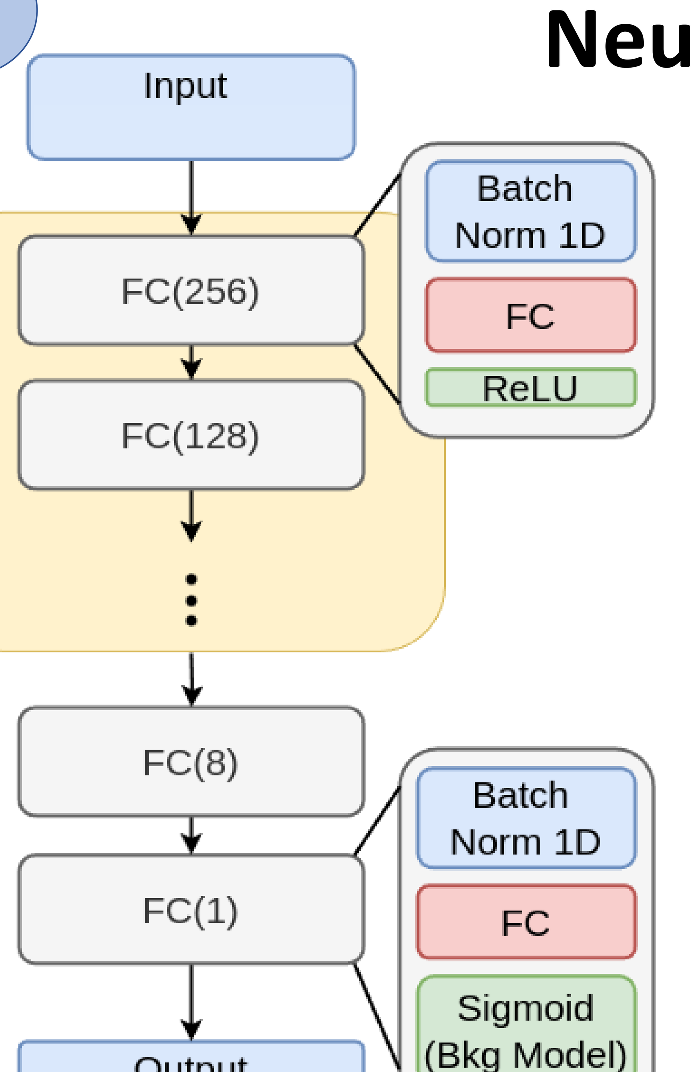
GRB Model

- Simulated bursts with Band function spectra [8]; α=-0.5, E_{peak}= 490 keV, β =-2.35
- Spectral energies in [30 keV-30 MeV] to approximately 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% (1σ) and 95% (2σ) *containment* values (i.e., 68/95% of trials yield at most given angular error)

4 Neural Networks

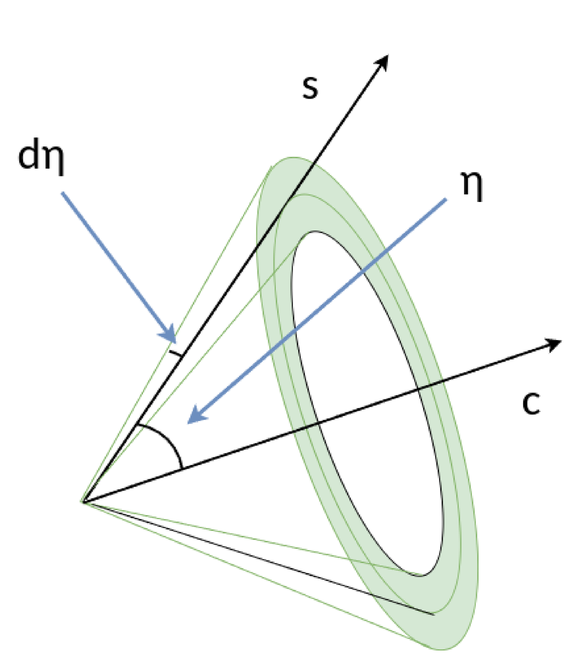


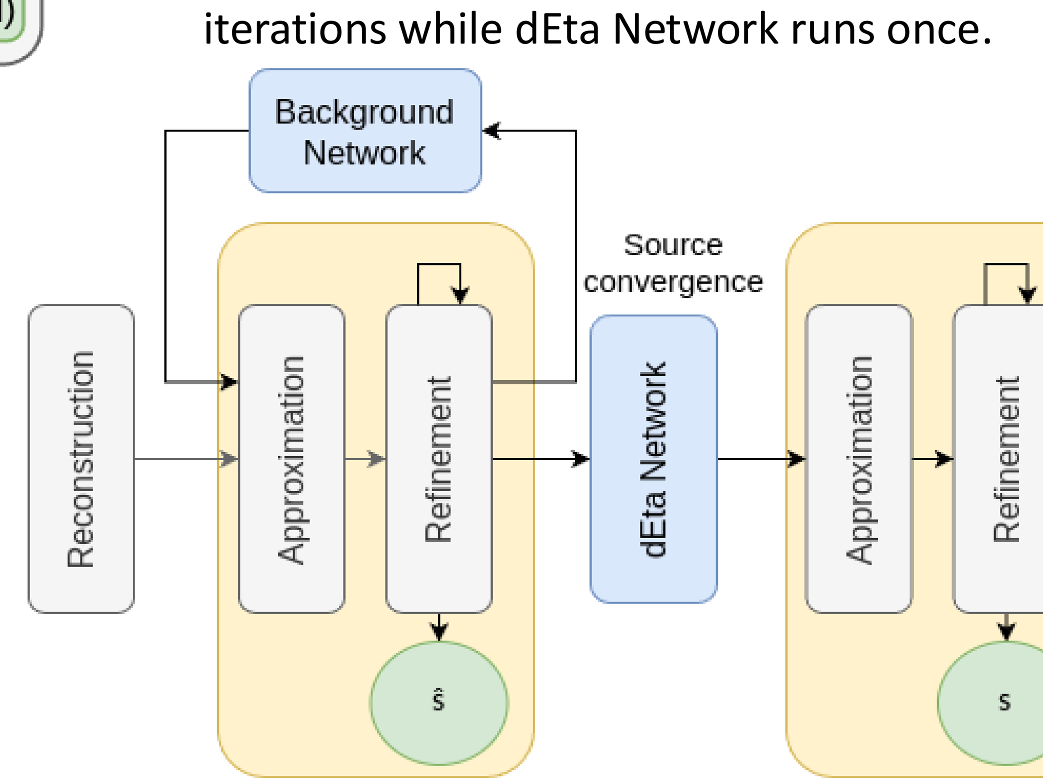
Network Architecture [13]

- BatchNorm-FC (fully-connected)-ReLU blocks motivated by [10].
- Estimated **s** as input (only polar component)
- Background Network: Classification of "background" rings
- dEta Network: Regression of ln(dη) of rings
- Tuned width, depth and shape of blocks (yellow region) separately for each network

Model Usage in Pipeline [13]

- Iterative between
  1. Traditional Algorithms
     - Approximation
     - Refinement
  2. Neural Networks
- Background Network loops for up to 5 iterations while dEta Network runs once.





3 Atmospheric Particle Background

Background Particles

In the Earth's upper atmosphere, ADAPT will be exposed to significant anisotropic background radiation from the Earth's limb [6]

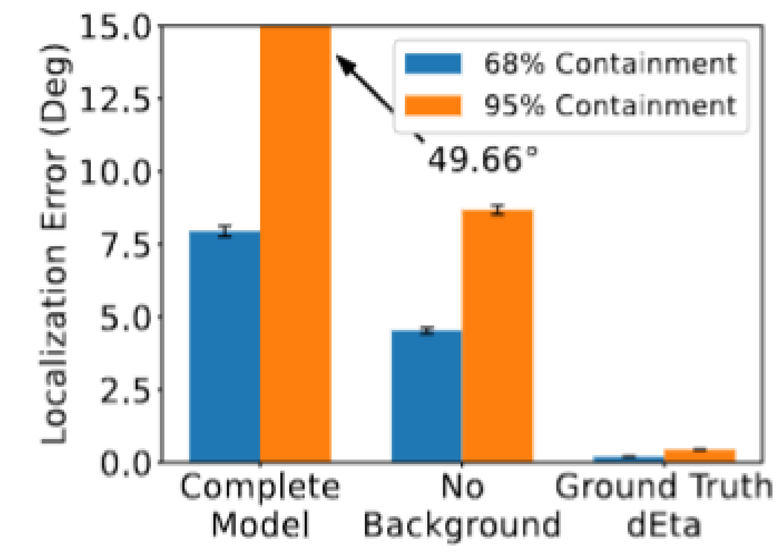
To filter out background events:

(1) Remove all events with two or more interactions occurring in the same layer

(2) Reject Compton ring lying entirely below the horizontal plane

Need for Networks (*right figure*)

- Baseline without Neural Networks
- The localization significantly improves
  (1) Without background
  (2) With ground truth dEta

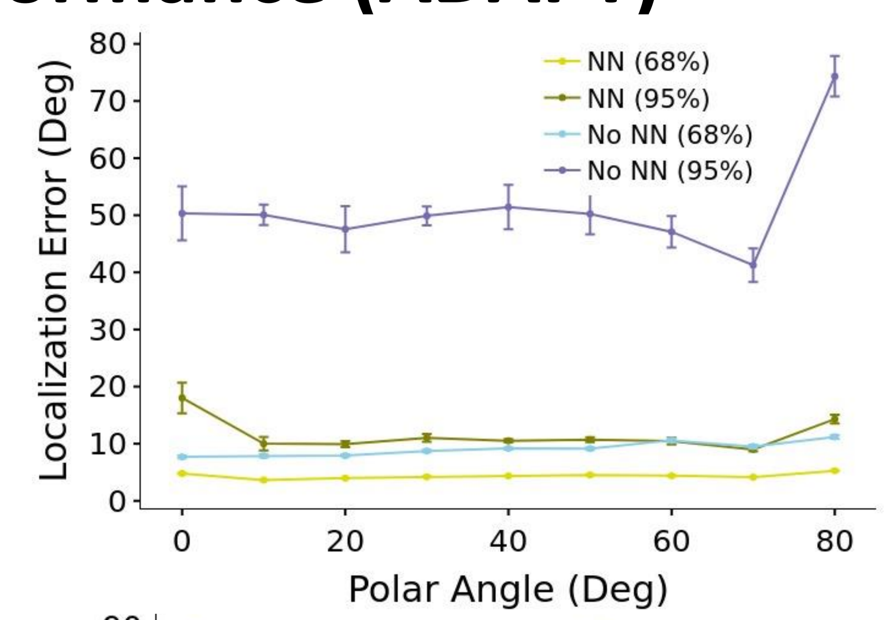


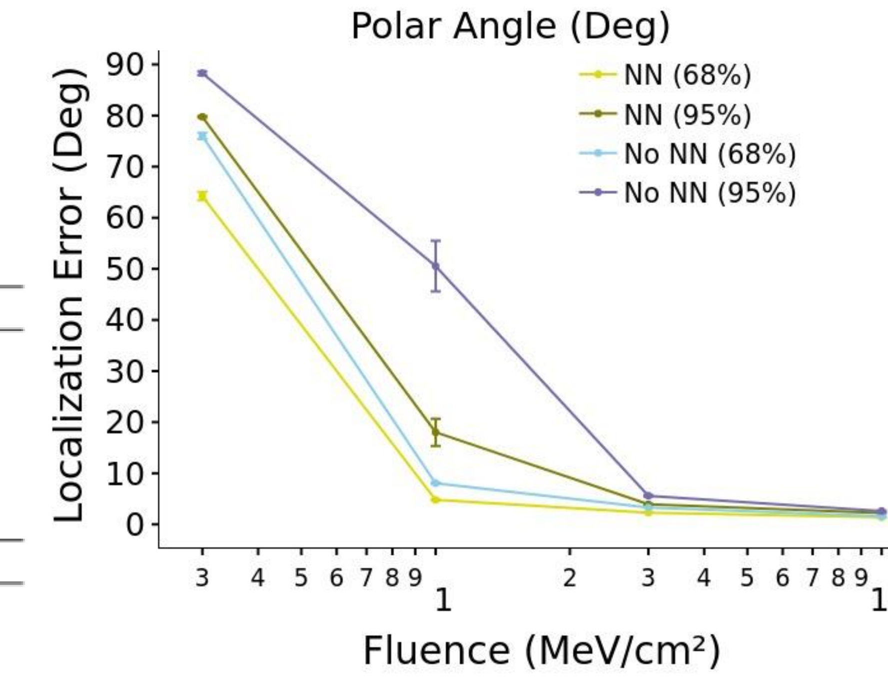
5 Localization Performance (ADAPT)

- Tested performance at incident polar angles (0°-80°) with 45° azimuthal angles
- At 1 MeV/cm^2, accuracy within **5-6°** 68% of the time for bursts well above the horizon (≤60°) (*top right figure*)
- For a normal burst, at fluences above 1 MeV/cm^2, accuracy below **6°**, 68% of the time (*bottom right figure*)
- Fast enough to run end-to-end on an embedded device < **1s**.
  - Intel Atom (flight computer on ADAPT): ~220 ms
  - Raspberry Pi3: ~840 ms

TIMING RESULTS ON ATOM.

Stage	Mean Time (ms)	Range (ms)
Reconstruction	18.6	15-26
Localization Setup	12.1	12-13
DEta NN Inference	5.5	5-6
Bkg NN Inference	14.7	14-15
Approx + Refine	18.5	17-21
Total (Max 5 iter)	220.7	204-246





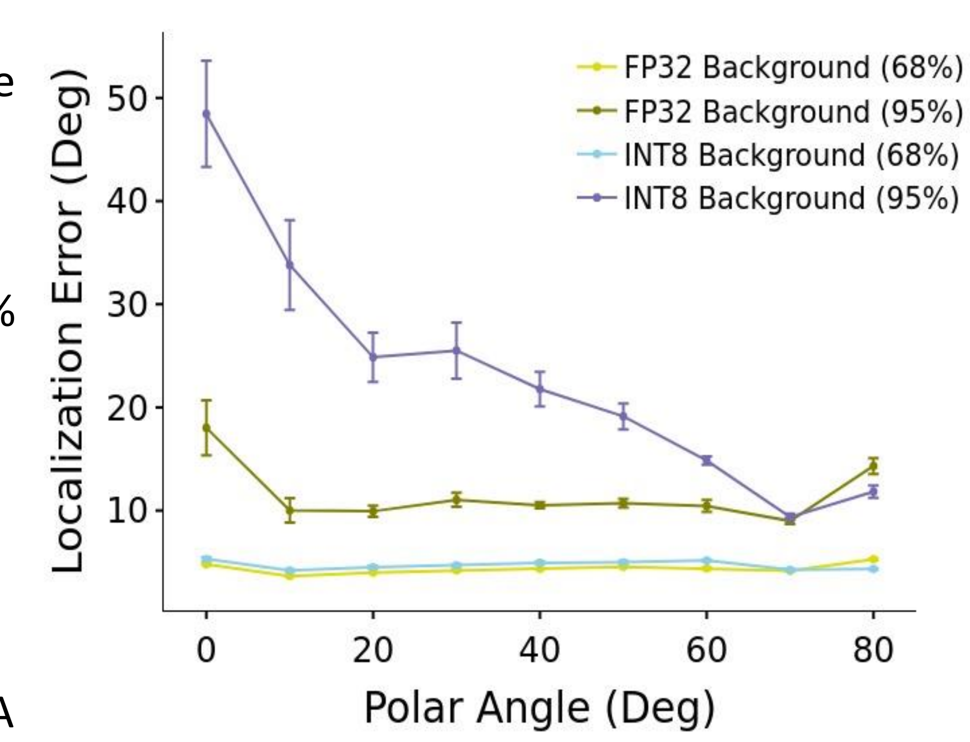
6 Quantization and FPGA

Quantization

- PyTorch's Eager Mode Quantization Aware Training (QAT)
- 'x86' default configuration
- FP32 to INT8
- 68% containment is similar, but the 95% containment got worse

FPGA implementation

- High Level Synthesis tool (Vitis HLS)
- Pipelined execution of layers
- For 597 rings (1 MeV/cm^2) **~4 ms** compared to 14-15 ms on the Atom
- **1.75×** the throughput of FP32 on the FPGA



7 Future Work

- **Better Quantization:** Test broader quantization strategies for better accuracy at 95% containment.
- **Generalized Networks:** Currently only tested for 45° azimuthal. Generalize the networks to handle all azimuthal angles.
- **Full Instrument (APT):** Extend the impact of our models on the full APT instrument which could allow localization of even dim (< 0.1 MeV/cm^2) GRBs to within a degree or less

[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.

[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.

[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.

[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, in Proc. of 38th International Cosmic Ray Conference, vol. 444, pp. 764:1–764:9, July 2023.

[6] 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.

[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.

[10] S. Takashima, H. Odaka, H. Yoneda, Y. Ichinohe, A. Bamba, T. Aramaki et al., Event reconstruction of Compton telescopes using a multi-task neural network, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 1038 (2022) 166897.

[11] 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.

[12] 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), Nov. 2023, pp. 395–398.

[13] 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 Wkshps. Int'l Conf. High Performance Computing, Network, Storage, and Analysis (SC-W), Nov 2024, pp. 4–10.