Real-time Likelihood Map Generation to Localize Short-duration Gamma-ray Transients

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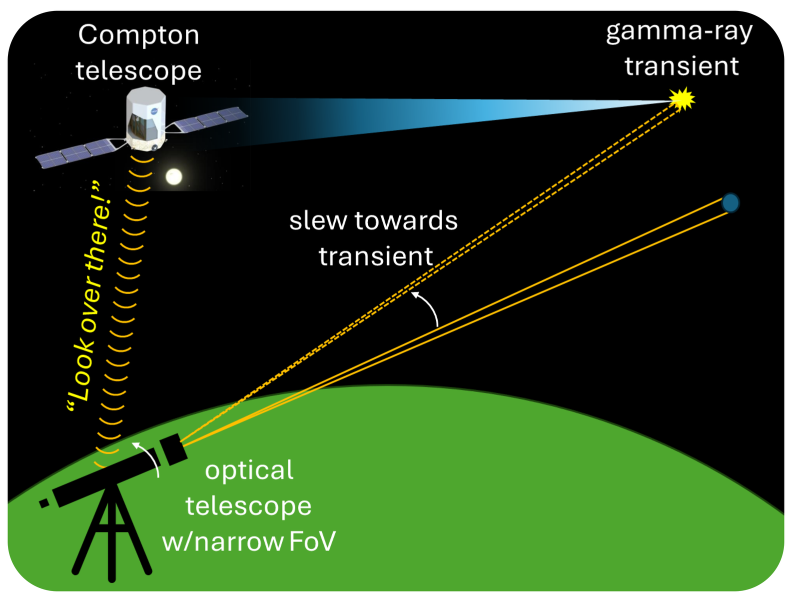
High-energy transient astrophysical phenomena, such as supernovae and binary neutron star mergers, benefit from a multi-wavelength investigation in which a space- or balloon-based omnidirectional telescope detects and localizes early high-energy emissions (e.g., a gamma-ray burst), then alerts a narrow-field-of-view follow-up instrument to observe the source. The high-energy telescope must provide a map that assigns to each sky location a likelihood that the source appears there. To issue prompt alerts despite limits on communication bandwidth and latency, it is desirable to compute these maps aboard the high-energy telescope, but doing so requires computing under stringent size, weight, and power constraints.

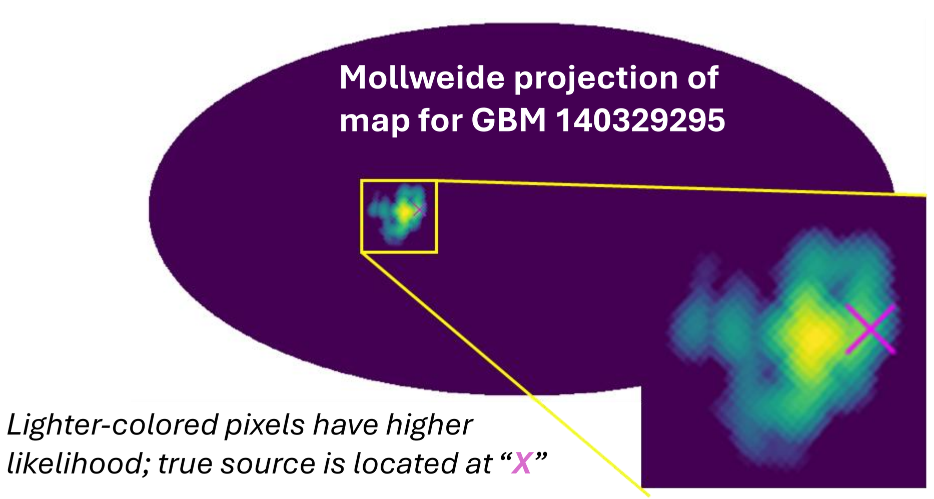
This work describes a real-time likelihood mapping implementation for Compton telescopes that is suitable for on-board computation. We use an adaptive multi-resolution approach and exploit data-reduction and parallelization opportunities to achieve sub-second construction of high-resolution maps (HEALPix N_{side}=64) using a detailed instrument response matrix on a low-power (< 10 W) embedded computing platform. We validate the speed and accuracy of our mapping approach on simulated gamma-ray transients from the third COSI Data Challenge [1].

The Task

- Compton telescope detects transient gamma-ray point source (e.g., GRB)
- Must **localize** source in the sky…
- … and **alert** cooperating telescope with narrow FoV to point towards it.



Uncertainty in direction $\vec{s}$ to source is expressed by **likelihood map** that scores each possible direction



Challenge

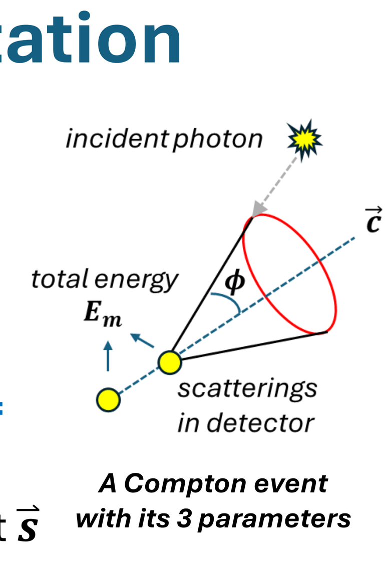
Provide actionable alerts to partner instrument **ASAP**!

Can we compute accurate likelihood map quickly (≤1s) and at high resolution (~1°)?

- To avoid latency and bandwidth limits of terrestrial computation, **compute maps in real time aboard Compton telescope**.
- Must operate with **low-power on-board hardware**.

Mapping Computation

- Given set D of ***Compton events*** $(E_m, \phi, \vec{c})$ produced by mix of **source photons** and **background radiation**
- For ***each*** possible source direction $\vec{s}$, compute **log likelihood ratio (LLR) of two hypotheses** given D:
  - H_s – D arises from mix of source at $\vec{s}$ and background
  - H_B – D arises from background only



LLR calculation requires two probabilistic models:

Instrument Response $R[\vec{s}, E_i, E_m, \phi, \vec{c}\,]$

defines $\Pr(E_m, \phi, \vec{c})$ *for source photons from* $\vec{s}$ *with energy* E_i

Background $B[E_m, \phi, \vec{c}\,]$

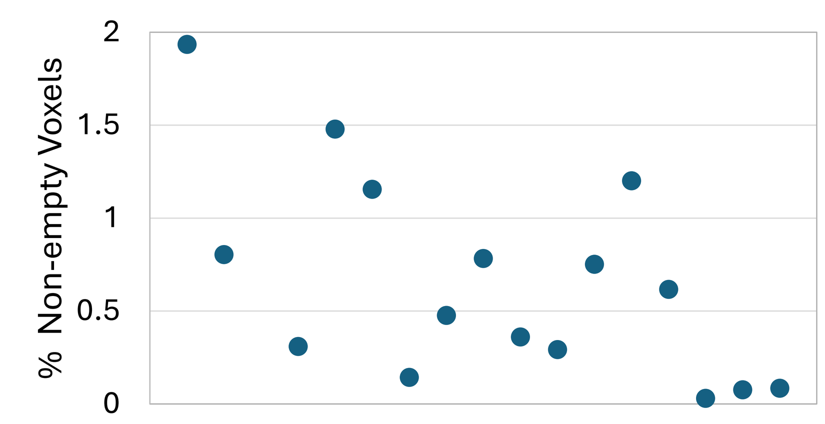
defines $\Pr(E_m, \phi, \vec{c})$ *for background particles*

Our LLR calculation follows binned Poisson approach with source intensity fitting from `cosipy` library [3].

Strategies for High Performance

1. Problem Size Reduction

- Space of possible $(E_m, \phi, \vec{c})$ is discretized into linear array of $10 \times 30 \times 768 \approx 2.3 \times 10^5$ *voxels*; **Cost of LLR computation is proportional to number of voxels**
- If no events of D fall within a voxel, it does not affect LLR

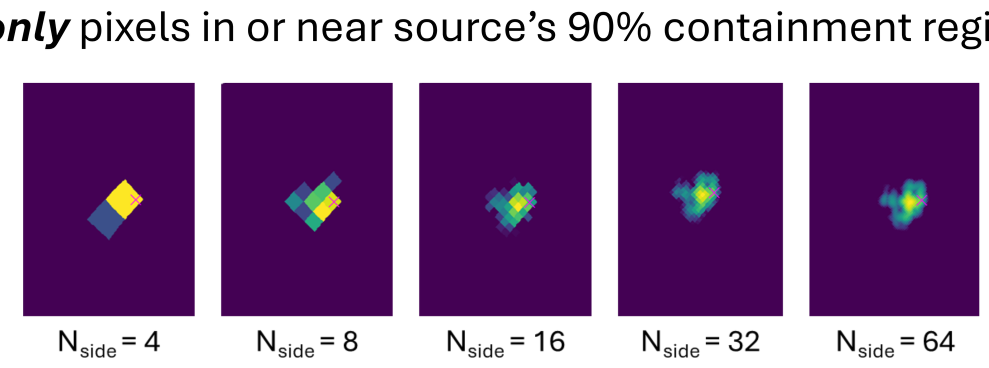


% Non-empty voxels for 16 transients from COSI Data Challenge 3

- ***Idea***: reduce R, B to **non-empty** voxels before mapping
- ***> 50x problem size reduction for all but brightest transients***; *does not require use of sparse matrices!*

2. Multi-Resolution Mapping

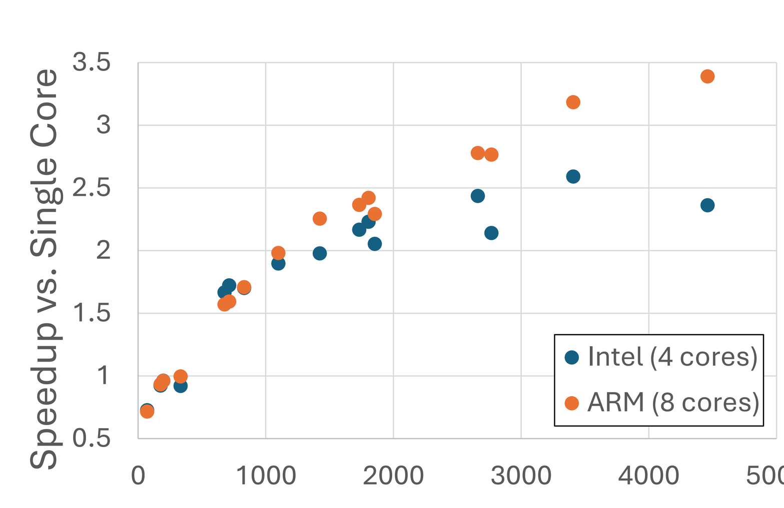
- Map is discretized into 49,152 pixels for $\vec{s}$ using HEALPix [4] (N_{side} = 64, < 1° resolution)
- Most pixels have **very low likelihood** relative to max
- Compute full map at N_{side} = 4 (192 pixels), then refine ***only*** pixels in or near source's 90% containment region



- Iterative refinement increases resolution 4x each time
- Computes map detail near likely source, yet *eliminates* **97-99%** *of computation* vs. full-resolution map

3. Parallelization

- Can parallelize LLR computation across map pixels $\vec{s}$ and/or voxels of Compton data space
- Our implementation uses **Python**. "Natural" high-level parallelism in $\vec{s}$ suffers from multi-process limitations
- Instead, parallelize only performance-critical loops via Numba JIT



- Some performance improvement (**2-3x** on 4-8 cores)
- Limited by small number of non-empty voxels for dimmer bursts, and by remaining sequential code
- ***Future***: recode in C++ to allow high-level multithreading

For more details, please see our proceedings paper at this link

Validation

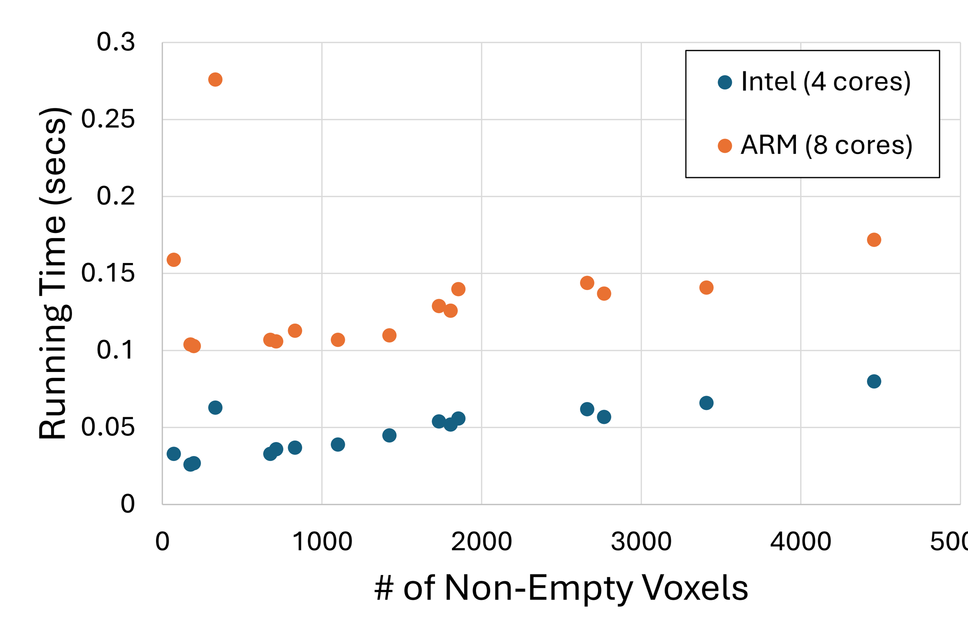
Data and Telescope Model

- Tested on 17 simulated transients from **third COSI Data Challenge [1]** – published GRBs and MGFs
- Simulated observation by **Compton Spectrometer and Imager (COSI) [4]**, incl. source + LEO background
- Discretized response R is $768 \times 10 \times 10 \times 30 \times 768$ (size in DRAM: 6.6 GiB)

Computing Platforms

1. Intel Core i7-13700TE – used aboard current and planned balloon-borne detectors
2. ARM Cortex-A78AE – Nvidia Jetson Orin NX (**peak power < 10 W**); closer to orbital capability

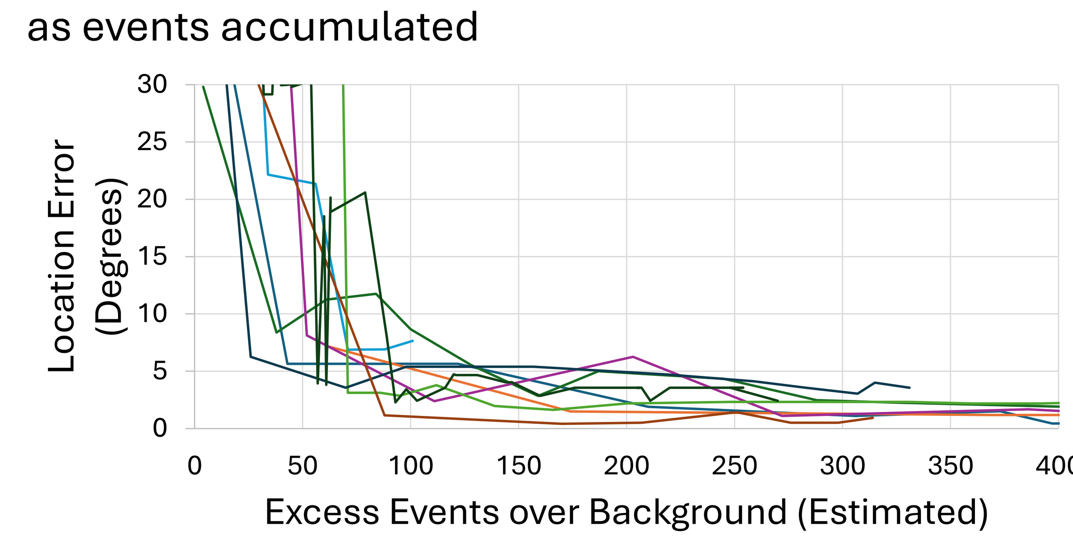
Running Time



- 16 low- to moderate-brightness DC3 transients mapped in **< 300 ms** on ARM, **< 100 ms** on Intel
- One bright GRB, GBM090424592, w/over 10^5 events needed 513 ms on ARM (not shown in figure)

Accuracy

- (***Disclaimer***: *results reflect our analysis pipeline,* ***not*** *inherent resolution of COSI*)
- Measured angular distance from maximum-likelihood map pixel to true source location
- For 7 short transients (< 2s), mean accuracy was **2.28°**
- For 9 long transients, generated new map each second as events accumulated



After seeing ~150 source events, typical accuracy was **within 5°**; final accuracy was **within 2°**

Conclusion

- **High-resolution source mapping is feasible in real time using low-power, on-board computing**
- *Facilitates rapid coordination between observers*
- *Key limitation*: resolution of instrument response R
- More detailed response possible but will require alternate, less memory-intensive representation

References

[1] Compton Spectrometer and Imager (COSI) Collaboration, COSI Data Challenges, Apr., 2025.10.5281/zenodo.15126188.

[2] K.M. Gorski et al., HEALPix: A framework for high-resolution discretization and fast analysis of data distributed on the sphere, *ApJ* 622 (2005) 759.

[3] I. Martinez et al., The cosipy library: COSI's high-level analysis software, in *Proc. of 38th Int'l Cosmic Ray Conf.*, vol. 444, pp. 858:1–858:8, 2023.

[4] J. Tomsick et al., The Compton Spectrometer and Imager, arXiv:2308.12362, 2023.