Design of Front-end Signal Processing for the Advanced Particle-astrophysics Telescope

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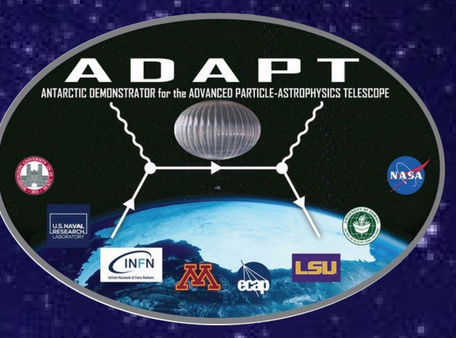
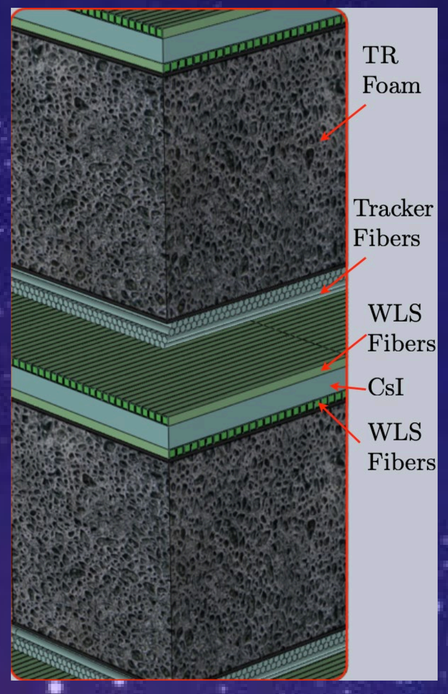
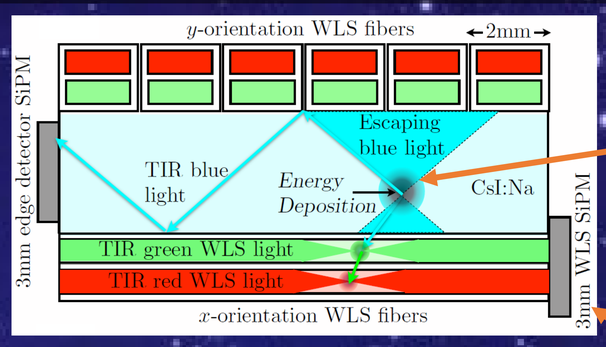


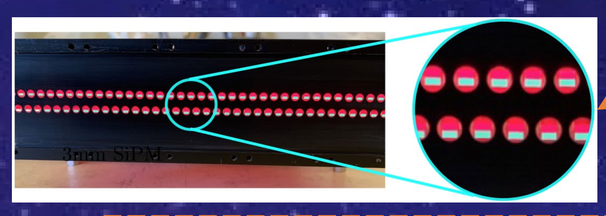
The Advanced Particle-astrophysics Telescope (APT) is a planned space-based observatory designed to detect and localize MeV transients such as gamma-ray bursts (GRBs) in real time. The goal is to enable concurrent, multi-messenger observation of transient GRBs from any direction with minimum delay. To keep latency low, the computational pipeline for detection and localization is fully onboard the instrument, which imposes significant size, weight, and power constraints.

For a mission overview, see Poster 103.45, "The ADAPT Mission"



APT will have 20 layers of 3x3m CsI:Na scintillating crystal
Orthogonal 2mm wavelength shifting (WLS) fibers are bonded to the top and bottom of each layer
Each layer is also coupled with orthogonal scintillating-fiber tracker hodoscopes

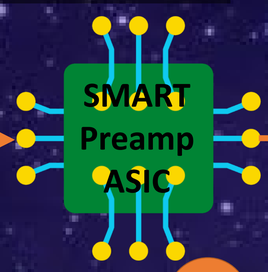


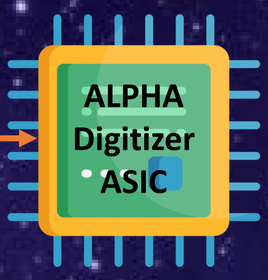


1 Gamma-ray photon Compton scatters or is photoabsorbed

2 Fibers capture light from CsI scintillation and transport to SiPM array

3 Preamplifier board shapes output from SiPMs



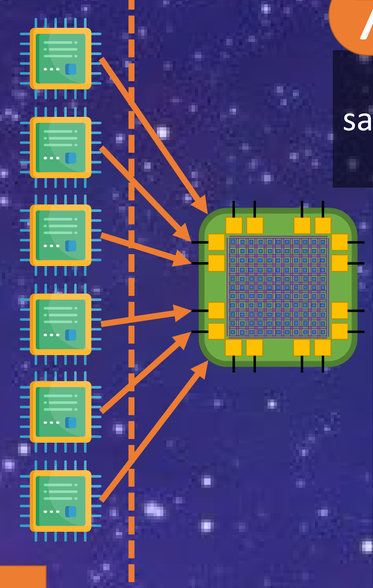


4 16-channel analog-pipeline waveform digitizer ASIC samples impulse response using 10ns windows

5 When triggered, ASICs read out buffer of 256 samples, A/D converted, to FPGA

Two incident gamma-ray photons arriving during the same readout window result in pileup

Our simulator models the pileup effects of short GRB time profiles and anisotropic atmospheric background for a balloon-borne Antarctic demonstration mission

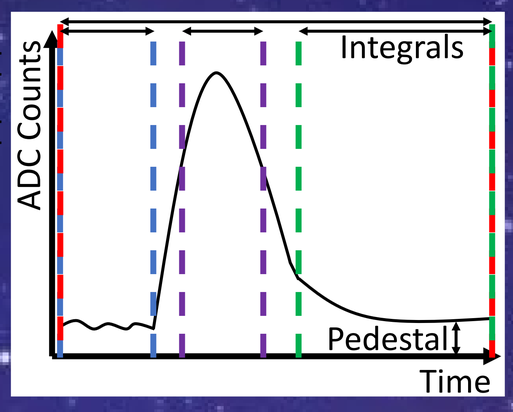


6 Pedestal Subtraction

ADC count contribution from analog memory pedestal must be subtracted

7 Signal Integration

4 integrals over subsets of 256 samples (2.56 μs) to capture complete time profile of CsI scintillation



Konst, Meagan. "Applying HLS to FPGA Data Preprocessing in the Advanced Particle-astrophysics Telescope." Masters thesis, Washington University in St. Louis, 2022.

- We applied high-level synthesis (HLS) to variable-offset pedestal subtraction and variable-length signal integration
- Target FPGA: Xilinx Kintex 7 XC7K325T-2FFG900C
- Synthesis and emulation: Xilinx Vitis software platform
- Results from current level of optimization:

# ASIC	FFs	% Util	LUTs	% Util	BRAM	% Util	Cycles	Latency
1	8,242	2.02	18,821	5.77	52	0.32	21,382	71.3μs
6	49,452	12.1	112,926	34.6	312	1.95		

- FPGA area not overutilized!
- However, latency exceeds 3μs target (holdoff time from trigger)

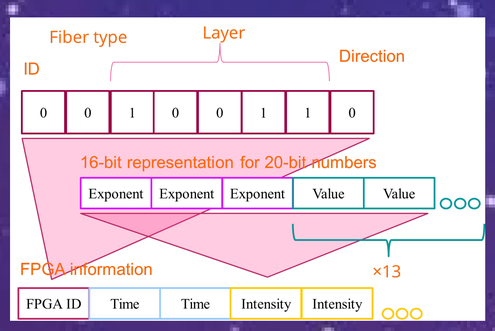
Future Work

- Use custom-width data types
- Incorporate dataflow pipelining and vectorization
- Burst copy data to the chip to minimize external DRAM access

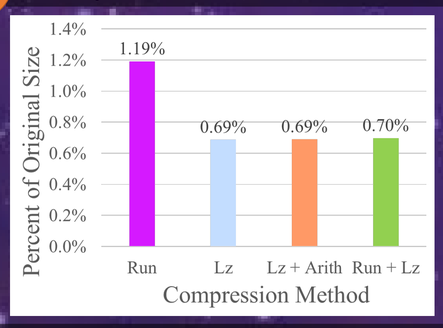
Compression

Compress integrated fiber intensities to send to CPU in addition to centroids for later analysis

C1 Represent 20-bit fiber data as 16-bit values. For intensity values up to 1 million, error remains less than 0.02%



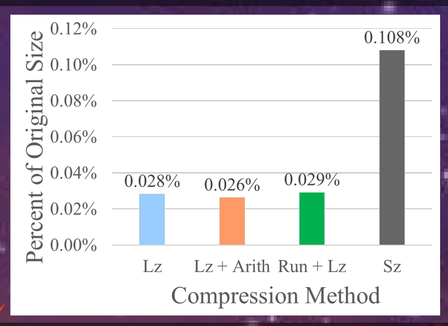
C2 Compress data, send to CPU



Conclusion

Off-the-shelf compression algorithms effective for Compton-regime data

C3 CPU decompresses data from each FPGA, then combines & recompresses



High fluence events:
- 62.42 MeV/cm^2
- 5.2×10^6 detected events
- Total compressed size: 42 MB

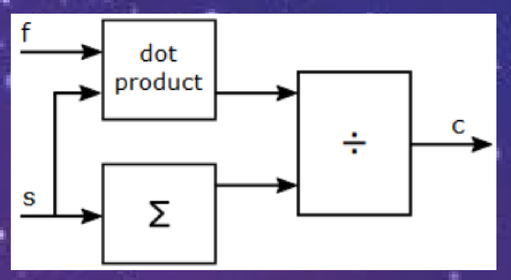
High flux events:
- 14.36 MeV/cm^2/s
- 1.12×10^6 detected events/s
- Data Rate (FPGA array to CPU): 830 Mbps

8 Centroiding

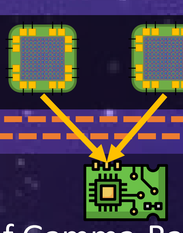
Original interaction locations and energies inferred from integrated fiber signal distributions.

HLS Implementation
- Find hit groups (contiguous fibers with nonzero signals)
- Determine weighted mean position within hit group
- Completes in 0.23μs (68 cycles), well under target latency

J Wheelock, W Kanu, M Sudvarg, Z Xiao, JD Buhler, RD Chamberlain, JH Buckley. "Supporting multi-messenger astrophysics with fast gamma-ray burst localization." UrgentHPC 2021.



Data reduced from 10ns samples to <x,y,z,E>
Centroids sent from >80 FPGAs to CPU performing backend computation



Backend Computation

For more details, see poster 103.29, "Prompt, Accurate Localization of Gamma-Ray Bursts in the Advanced Particle-astrophysics Telescope"

9 Event Reconstruction

Centroids from each individual gamma ray are combined and used to reconstruct Compton angles

10 GRB Localization

Resulting annuli describing PDF of incoming source direction are intersected to infer a common source

This work funded by NASA grant 80NSSC21K1741 and NSF grant CNS-1763503