(EFFICIENTLY) Mining Antarctica for Cosmic Neutrinos

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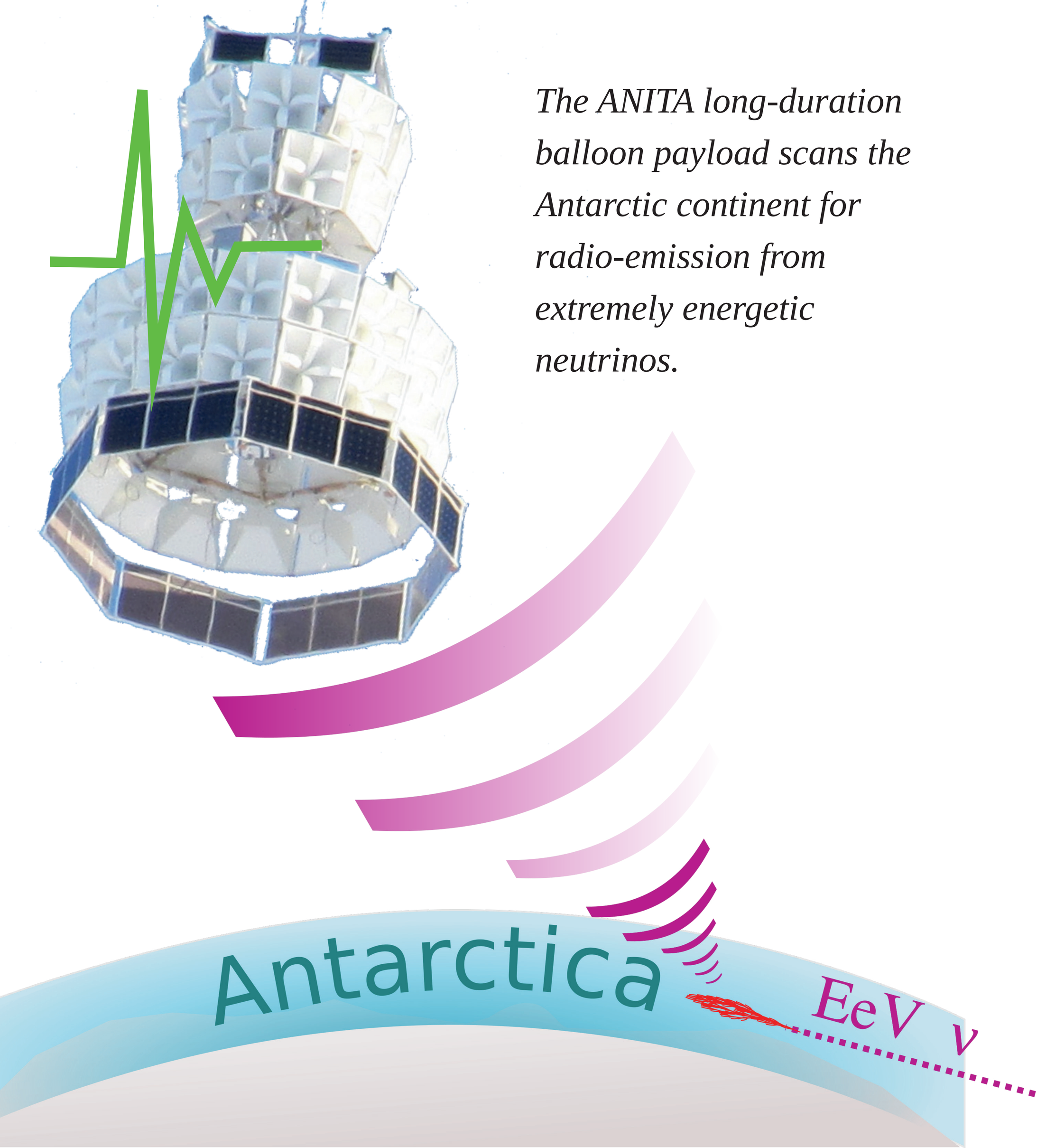
Image: NASA/Blue Marble

The ANITA Experiment



The ANITA long-duration balloon payload scans the Antarctic continent for radio-emission from extremely energetic neutrinos.

Interactions of ultra-high-energy cosmic rays with the Cosmic Microwave Background are expected to produce a flux of extremely energetic "cosmogenic" neutrinos. Successful detection would shed light on the acceleration mechanisms that produce cosmic rays and probe our knowledge of particle physics at the highest energies.

Due to their low expected flux and small interaction cross-section, a massive detection volume is necessary to have a chance of measurement. One practical means of instrumentation is to search for radio-emission from high-energy neutrinos interacting in a dielectric medium, such as glacial ice.

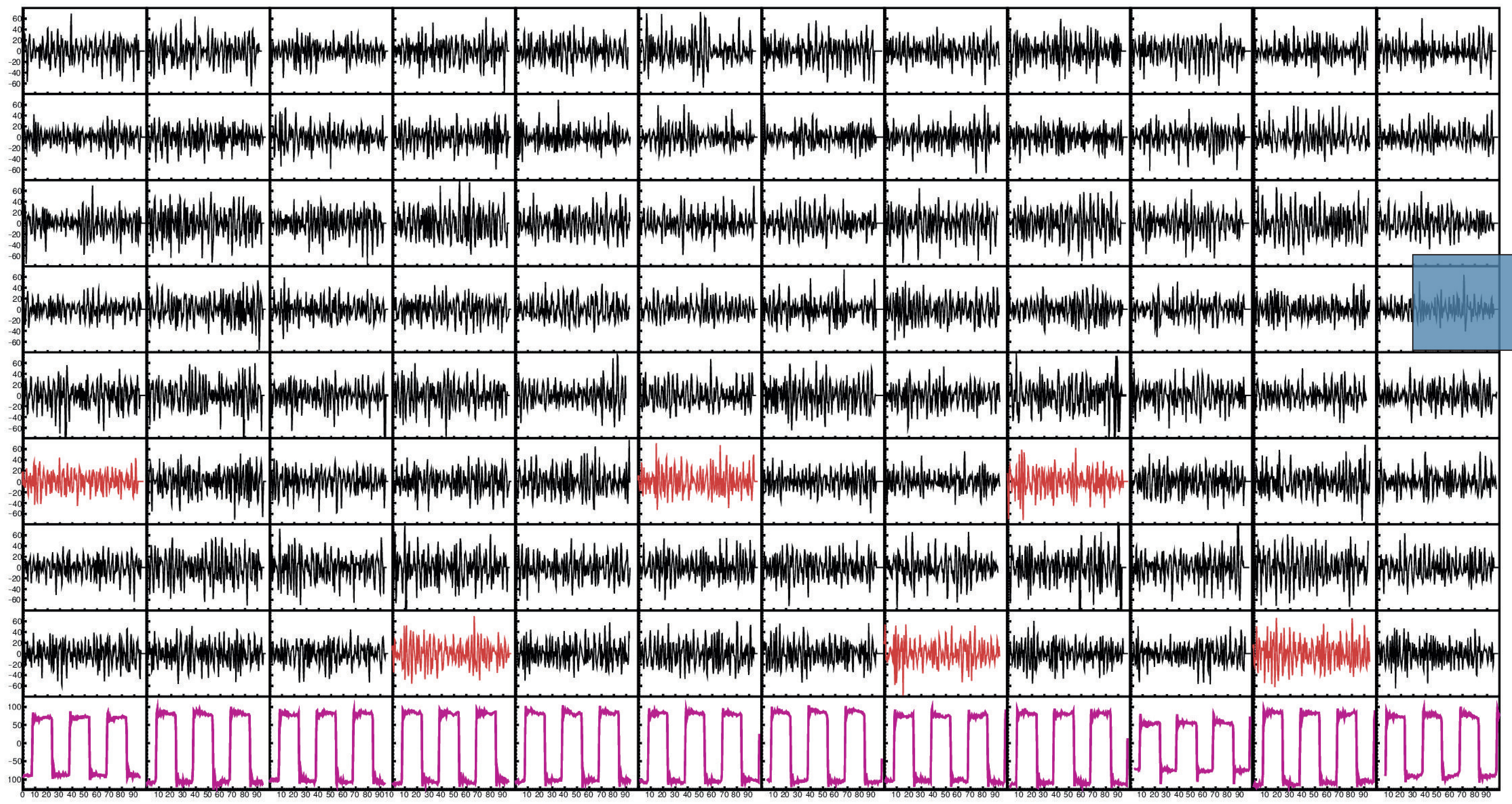
The ANtarctic Impulse Transient Antenna (ANITA) balloon-borne payload flies at 35-40 km over Antarctica, instantaneously scanning approximately 10^6 km^3 of ice for impulsive radio emission from cosmogenic neutrino interactions. Any neutrino signal must be extracted from an overwhelming background of thermal noise and anthropogenic activity. The third (Dec 2014-Jan 2015) and fourth (Dec 2016) flights of ANITA are currently being analyzed at the University of Chicago using RCC resources.

The ANITA-4 launch in December 2016, near McMurdo Station, Antarctica. At float altitude (35-40 km), the balloon has a diameter of 100 m.

Data

ANITA's trigger is designed to detect impulsive radio emission within its band (180-1200 MHz). When triggered, traces corresponding to the electric fields received by each of the 96 antennas on the payload are recorded. Each trace is approximately 100 ns long, sampled at 2.6 GS/s. The trigger thresholds are dynamically adjusted to maintain as high an event rate as possible without significant deadtime (~50 Hz). ANITA-3 and ANITA-4 both recorded around 100 million events over their several-week flights, corresponding to over 2 TB (compressed) of physics data for each flight.

Nearly all traces are thermal noise or anthropogenic emission from communications satellites or Antarctic bases. Some events, like the one below, come from calibration pulsers deployed around the continent. Among the millions of events, we expect to find at most several cosmogenic neutrinos. We also expect to see radio emission from tens of cosmic rays.



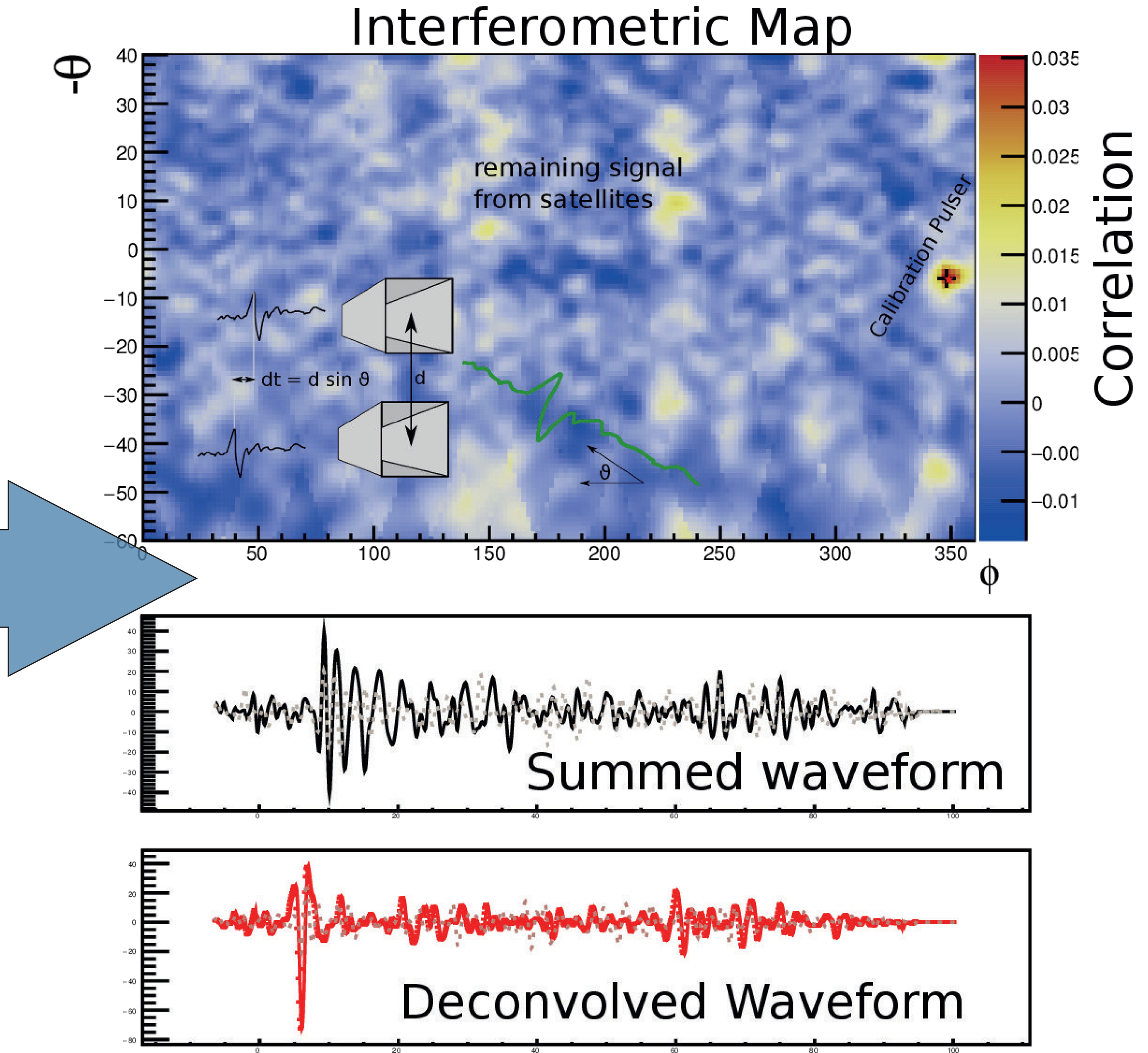
Digitizer traces from a calibration pulser event in West Antarctica. Each column corresponds to a digitizer chip, each row to a channel (the bottom is a clock). The units on the y-axis are mV and on the x-axis are nanoseconds. The channels in red contributed to the trigger.

Computation

github.com/anitaNeutrino/

The ANITA analysis tool chain is implemented in C++ using the `ROOT` framework with performance in mind. In addition to data-level parallelism, per-event parallelism is implemented with `OpenMP`. This allows faster interactive analysis of single events for diagnostic purposes and reduces overall IO overhead. `fftw3` is used for efficient Fourier transforms.

Identified bottlenecks have gradually been removed with improved algorithms, caching, preload/branch-prediction hints, and manual SIMD vectorization.



(Top) Interferometric map corresponding to the traces on the left. The brightest spot is the primary pointing hypothesis. (Bottom) The coherently summed waveform is formed by summing up antennas in that direction with the appropriate delays. The deconvolved waveform removes the dispersion from the signal chain.

Step 0: Resampling

ANITA digitizers sample with unequal time increments. Efficient signal processing requires even sampling, so spline interpolation is used to approximate the evenly sampled signal. Akima splines are a compromise between more accurate regularized matrix inversion techniques and more efficient linear interpolation.

Step 1: Filtering

Continuous-wave (CW) emission from satellites and bases are always present and must be removed from every event. However, the short traces are problematic for standard signal processing filters. We have developed an efficient time-domain sinusoid subtraction method that removes most CW while retaining the fidelity of desired signals.

Step 2: Interferometry

We expect our signal to consist of impulsive plane waves. Each incoming direction corresponds to a set of time delays between ANITA's antennas. We use these delays to build a map of antenna correlation as a function of incoming direction, which we use to identify sources. The correlations are performed in the frequency domain.

Step 3: Classification

Coherently summed and deconvolved waveforms are computed for the best pointing hypotheses. Features of the waveforms are used to reject thermal noise and remaining CW. A false positive rate of $O(10^{-7})$ is required to discover cosmogenic neutrinos. Machine learning techniques (through TMVA) are being used to optimize classification.

Step 4: Clustering

Remaining events at this stage are impulsive anthropogenic backgrounds and physics candidates. Anthropogenics are assumed to cluster in position to known bases or to each other, so the final step is to look for isolated impulsive events.