Interferometric Techniques for Radio Impulses from Ultra-high Energy Particle Showers

Andres Romero-Wolf for the ANITA Collaboration

Jet Propulsion Laboratory,

California Institute of Technology

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Radio Interferometry is a Prevalent Technique

Radio detection of ultra-high energy particles is a newcomer to radio interferometry.

An interdisciplinary workshop was held at OSU in April, 2013 bringing interferometry experts across various scientific disciplines.

Radio interferometry workshop at OSU, April 2014

CCAP Interferometry Workshop

http://ccapp.osu.edu/workshops/RadioSim2/workshop.html

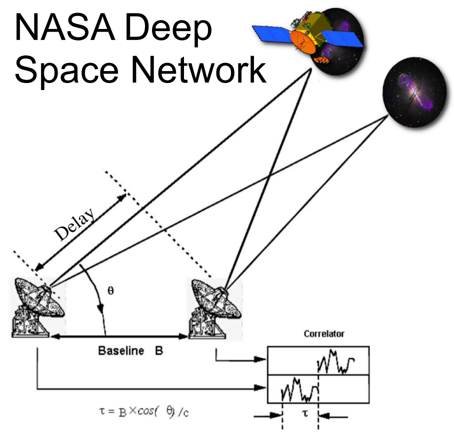
Inter-continental VLBI

200 µas astrometric resolution.

This resolution enabled landing of MSL!

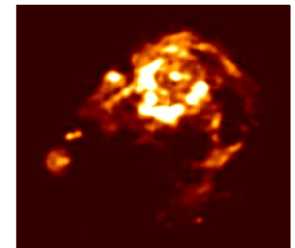
C. Naudet, JPL

NASA Deep Space Network



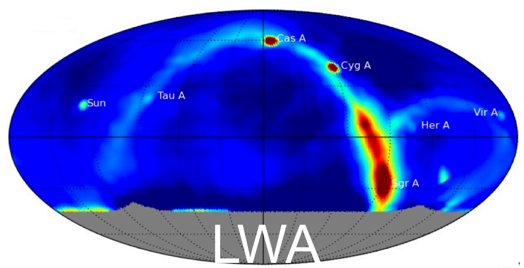
State of the art radio source imaging.

S. Bhatnagar, NRAO



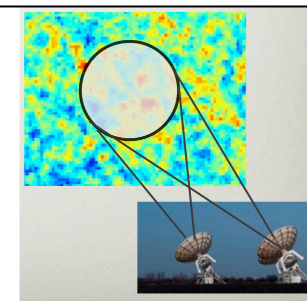
All-sky imaging of radio transients.

J. Hartman, JPL (now at Google)



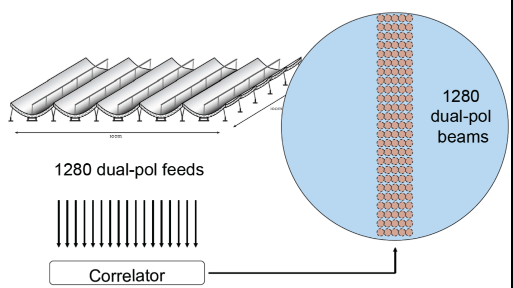
CMB polarization measurements

L. Zhang, UW



CHIME interferometer for 21 cm line cosmology

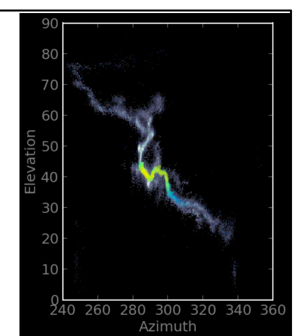
K. Bandura, McGill



Spatio-temporal imaging of lightning.

http://vimeo.com/62892536

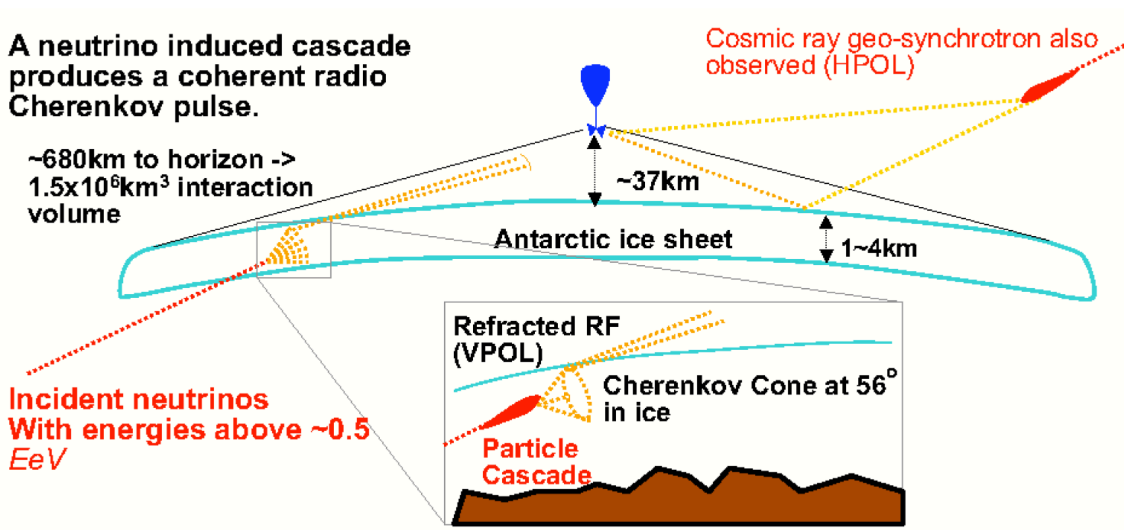
M. Stock, NMT



Application of Interferometry to Ultra-high Energy Particle Astrophysics

The ANITA Ultra-high Energy Particle Telescope

- Synoptic horn antenna array (200-1200 MHz)
- Circumpolar trajectory on a balloon.

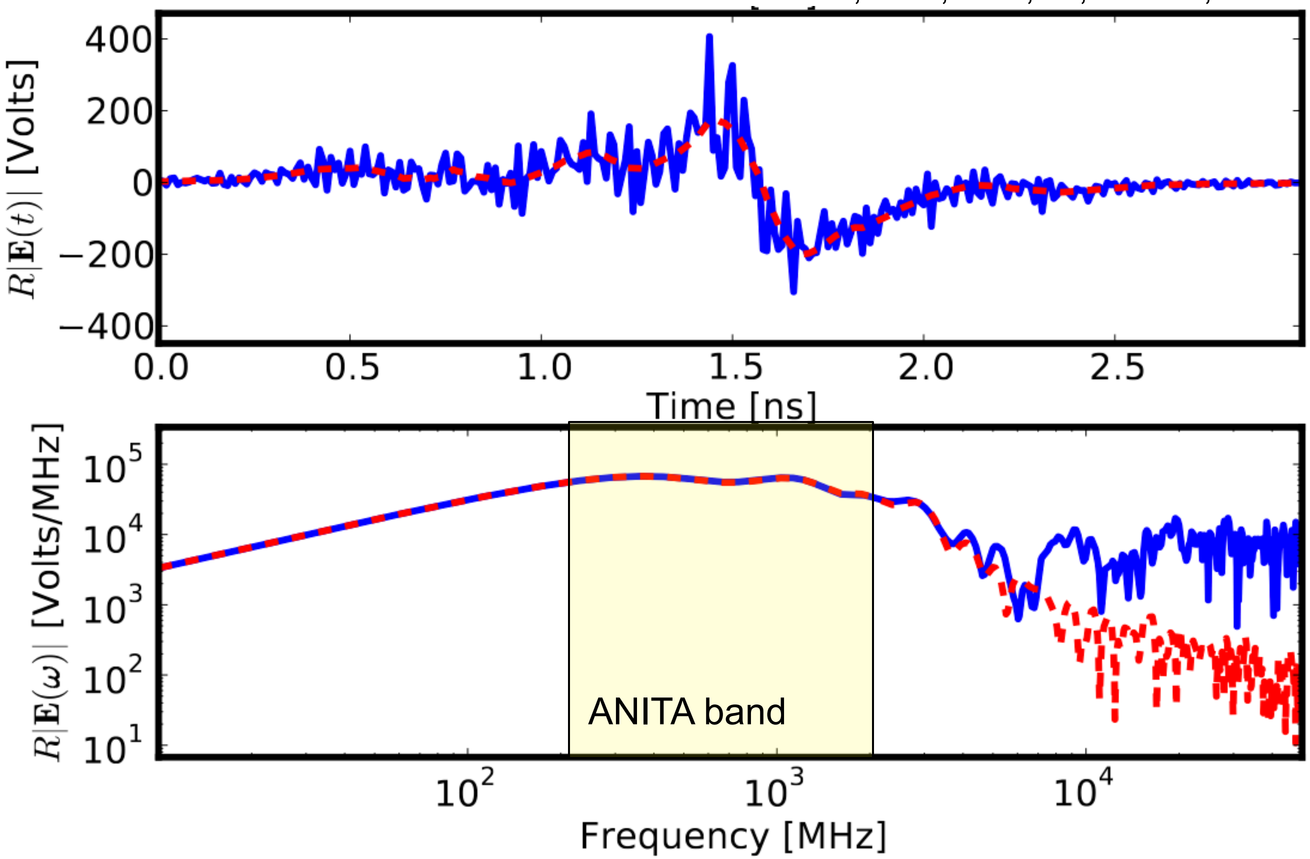


M. Mottram, PhD Thesis

P. Gorham et al., PRD, 82, 02204, 2010

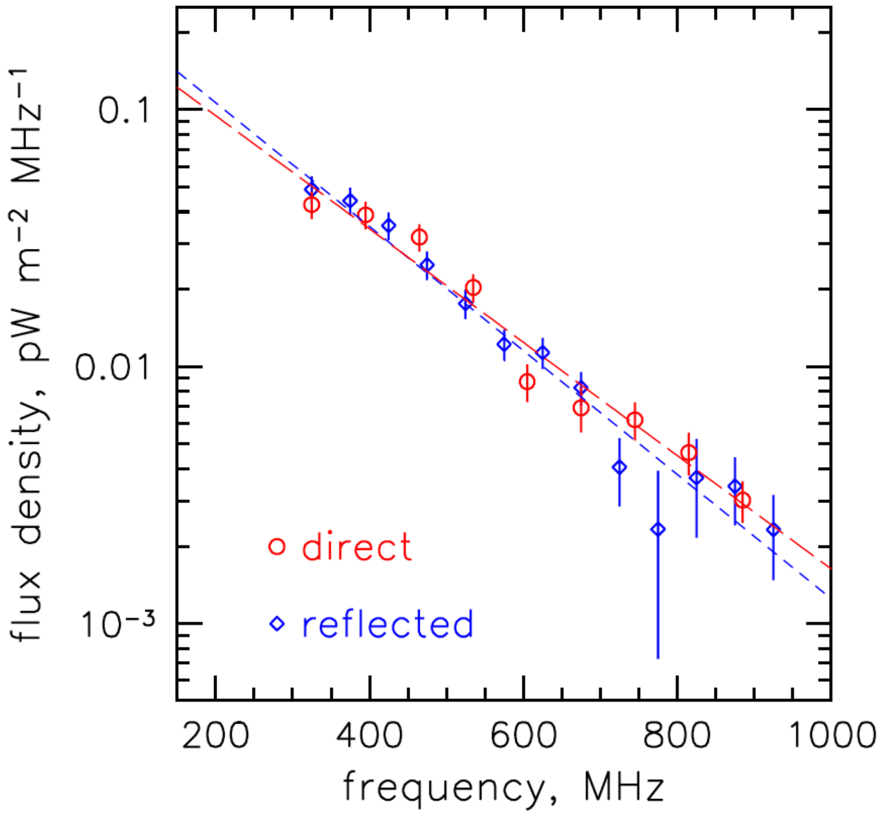
The Expected Signal Askaryan Radiation

Alvarez-Muñiz, et al., PRD, 84, 103003, 2010

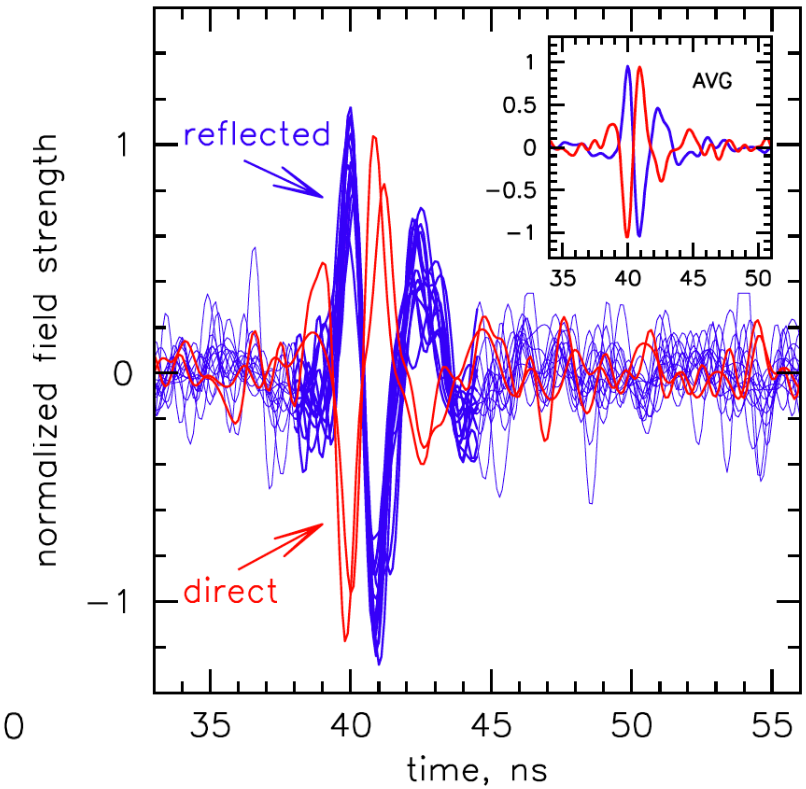


Blue includes incoherent high frequency emission (exaggerated by thinning)
Red is the high frequency filtered pulse.

The Unexpected Signal Geosynchrotron Radiation



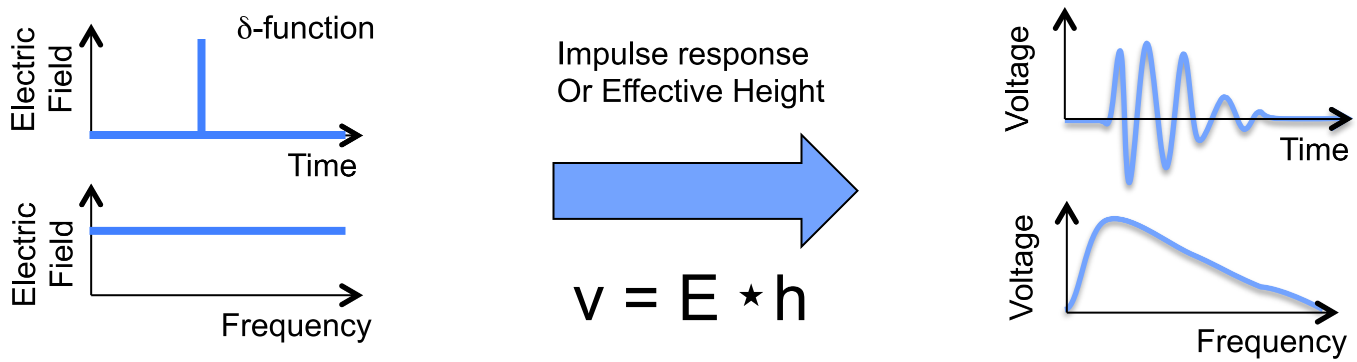
Hoover at al., 2010, PRL, 105, 151101, 2010



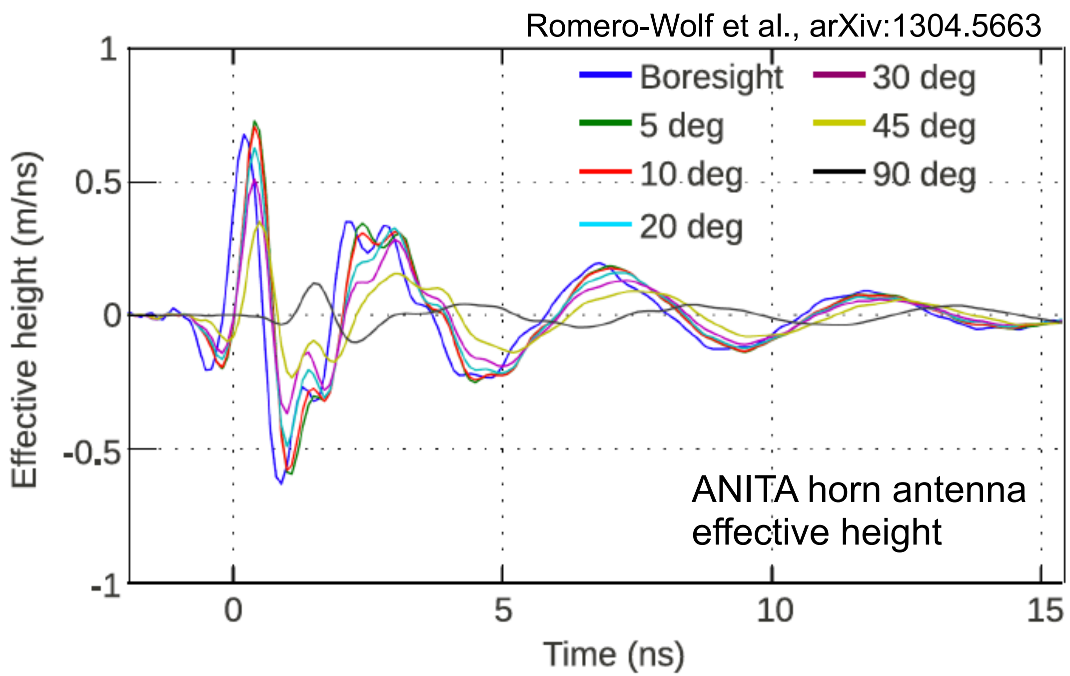
- Detected with ANITA in UHF band (200-1200 MHz).
- ANITA-3 (2014) will be tuned to detect hundreds of events.

Interferometric Technique Developed for Ultra-high Energy Particle Radio Impulses

Impulse Response

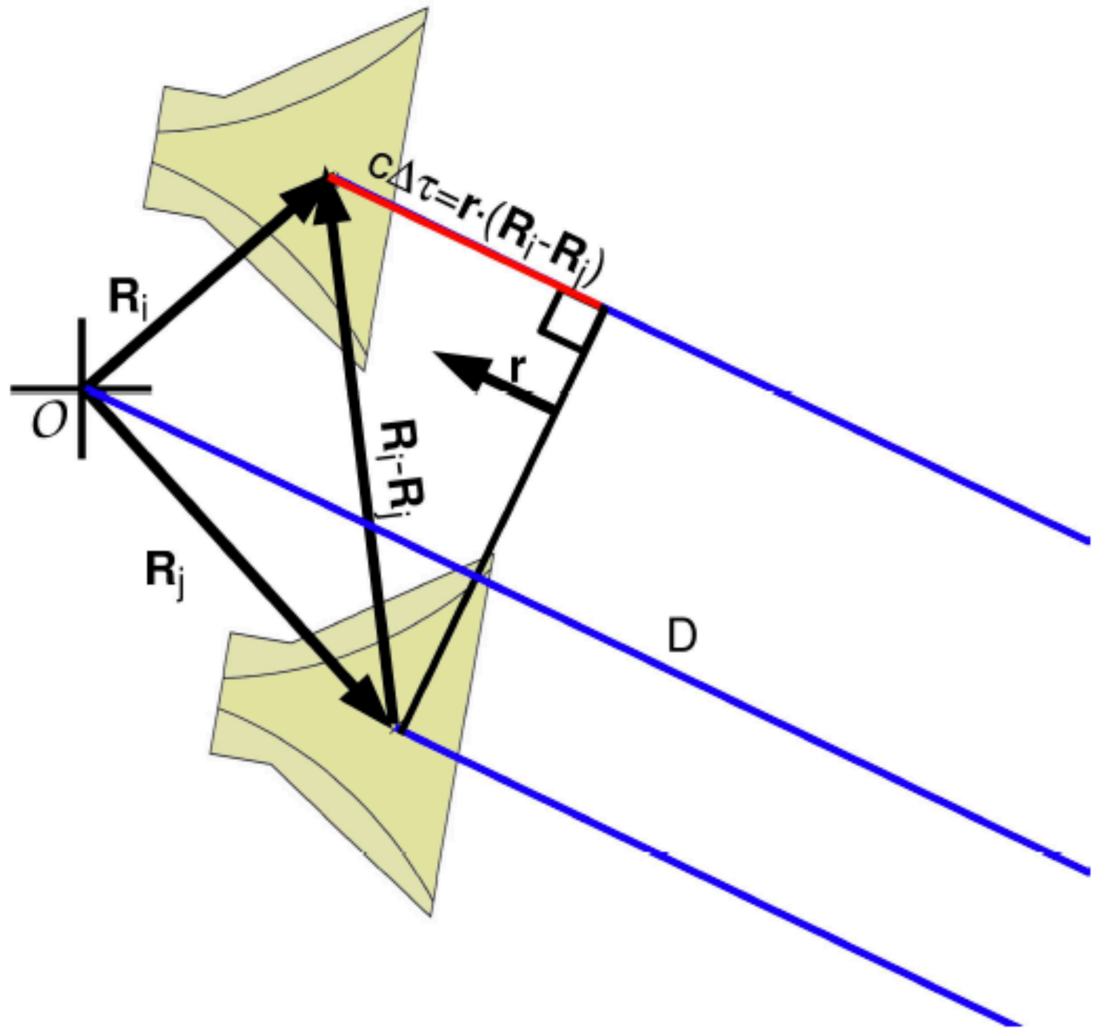


$$v = E \star h$$



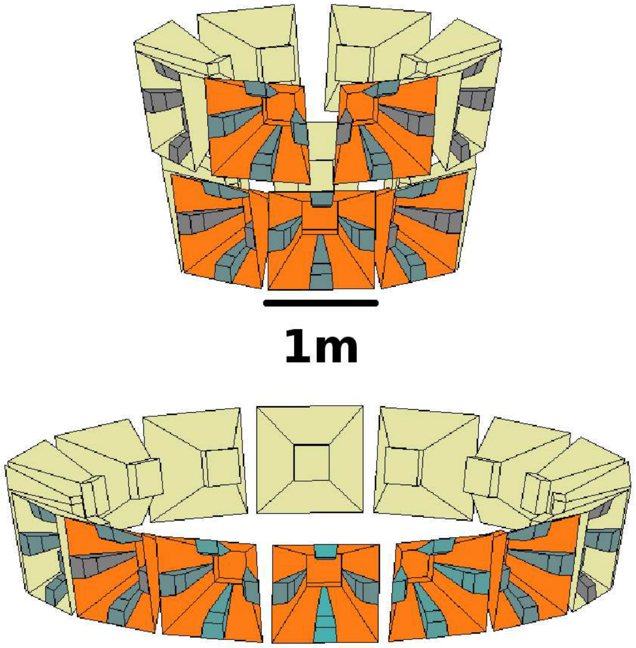
Geometric Delay

- Beam forming combines the signals from multiple antennas.
- The geometric delay is the basic quantity that connects multiple observations of the same signal.

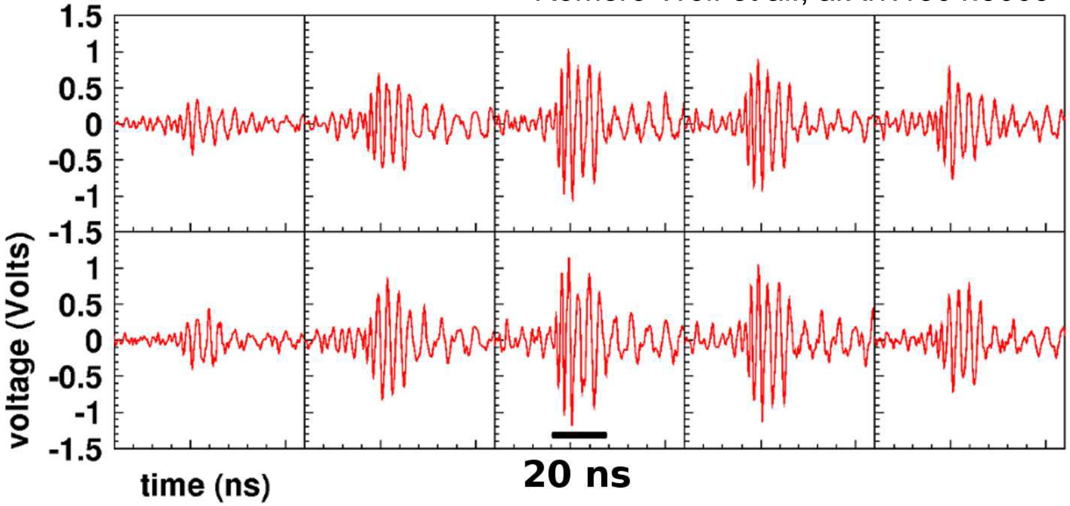


Romero-Wolf et al., arXiv:1304.5663

The ANITA Array



Romero-Wolf et al., arXiv:1304.5663



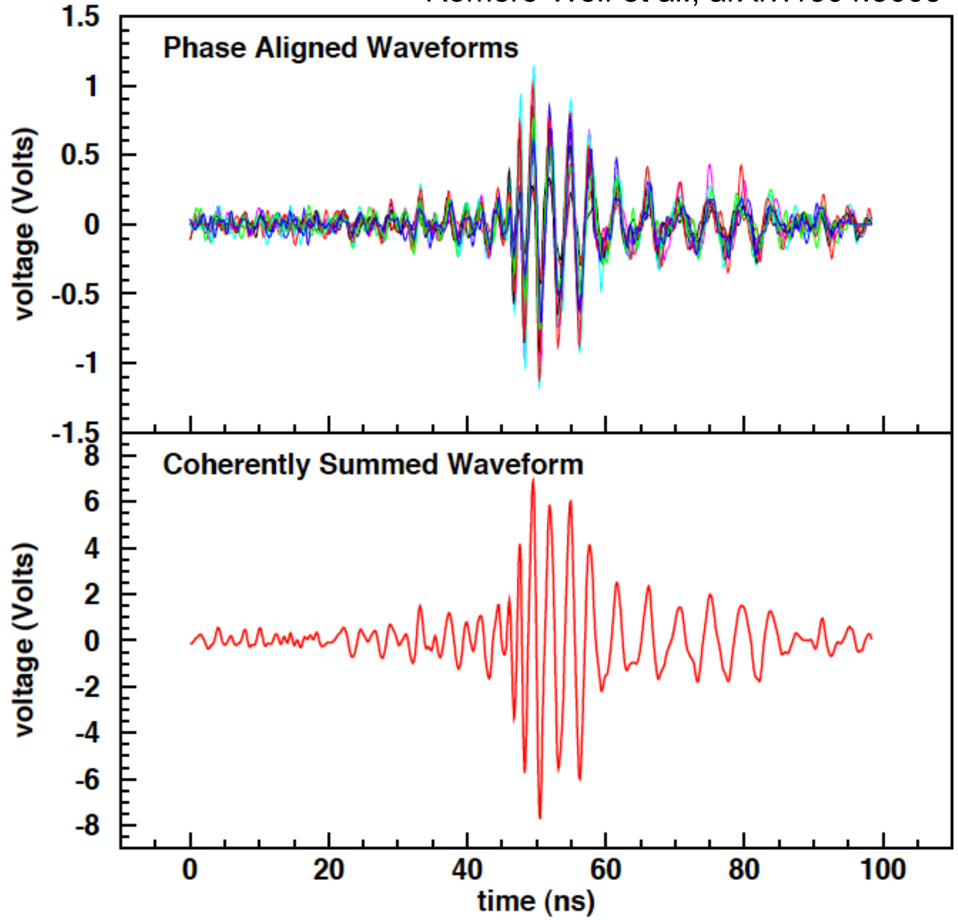
- ANITA antenna array observes the same impulse with multiple channels.
- The array is unusual in that the antennas are not all pointed in the same direction.
- The arrangement is designed for full azimuthal coverage.

Beam-forming

The signals from the previous slide are aligned in time according to the true geometric delay of the signal.

The directional response of the antennas does not affect the phase of the signal and it can be added coherently.

Romero-Wolf et al., arXiv:1304.5663

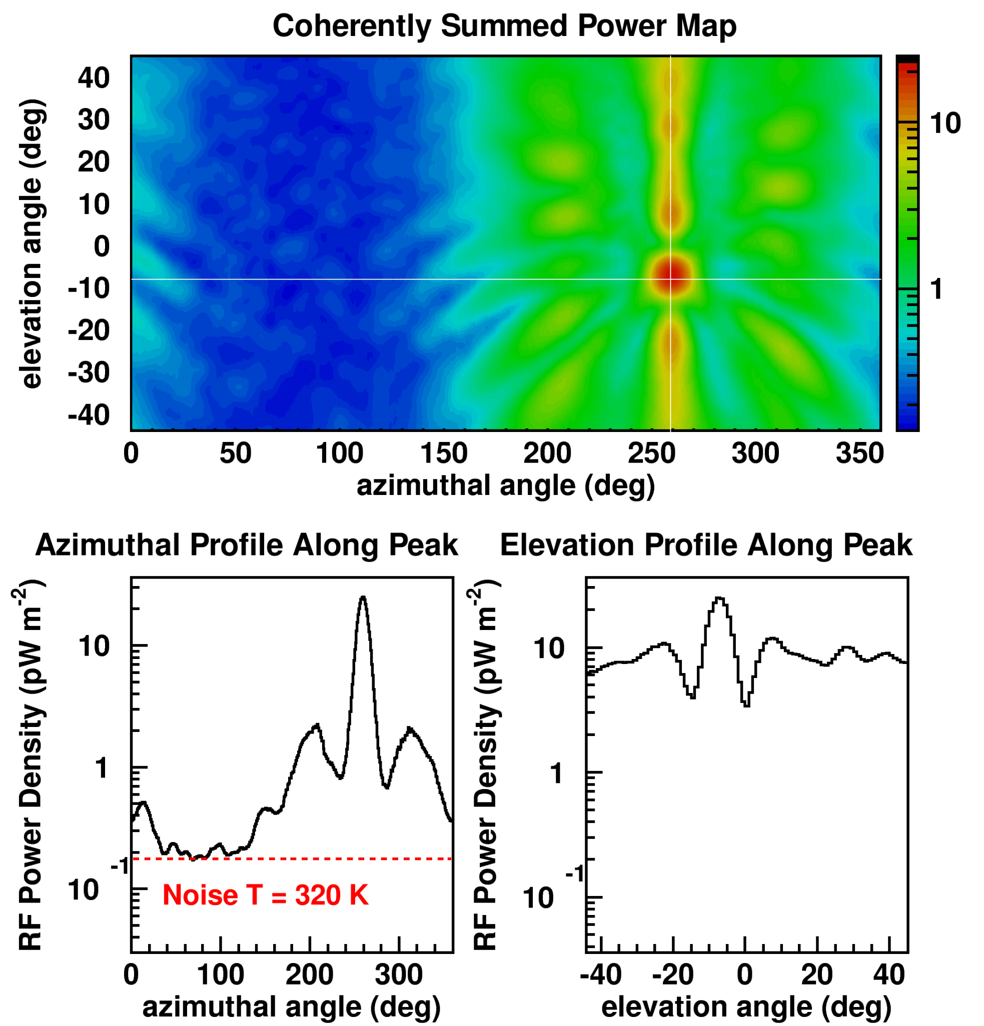


Coherently Summed Waveform Power

Global image of the coherently summed power for each assumed direction of the incident radiation.

The direction of true incidence presents itself as a sharp peak.

The diametrically opposed direction sees the thermal noise background.

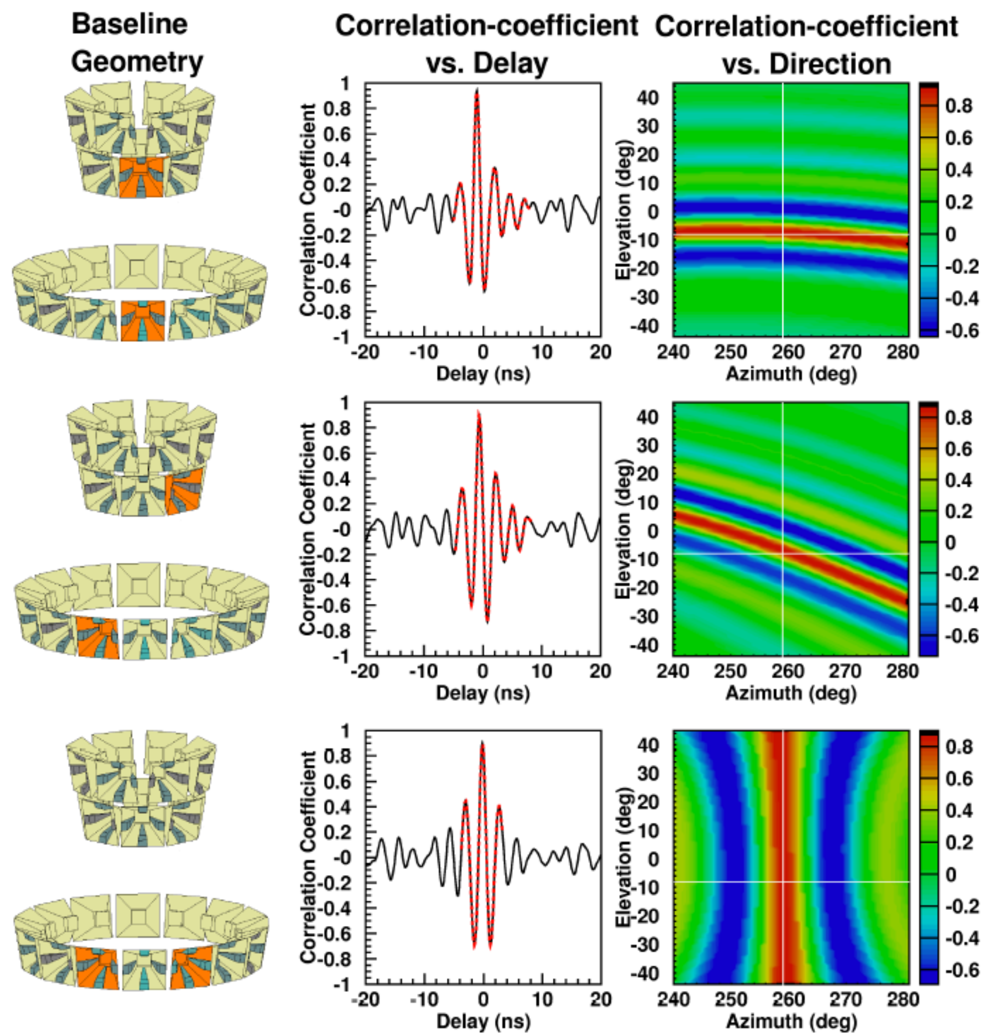


Romero-Wolf et al., arXiv:1304.5663

Beam-forming with Cross-correlations

Cross-correlations of an impulsive signal event.

The time-domain cross-correlation is mapped to incident direction via the geometric delay relation.



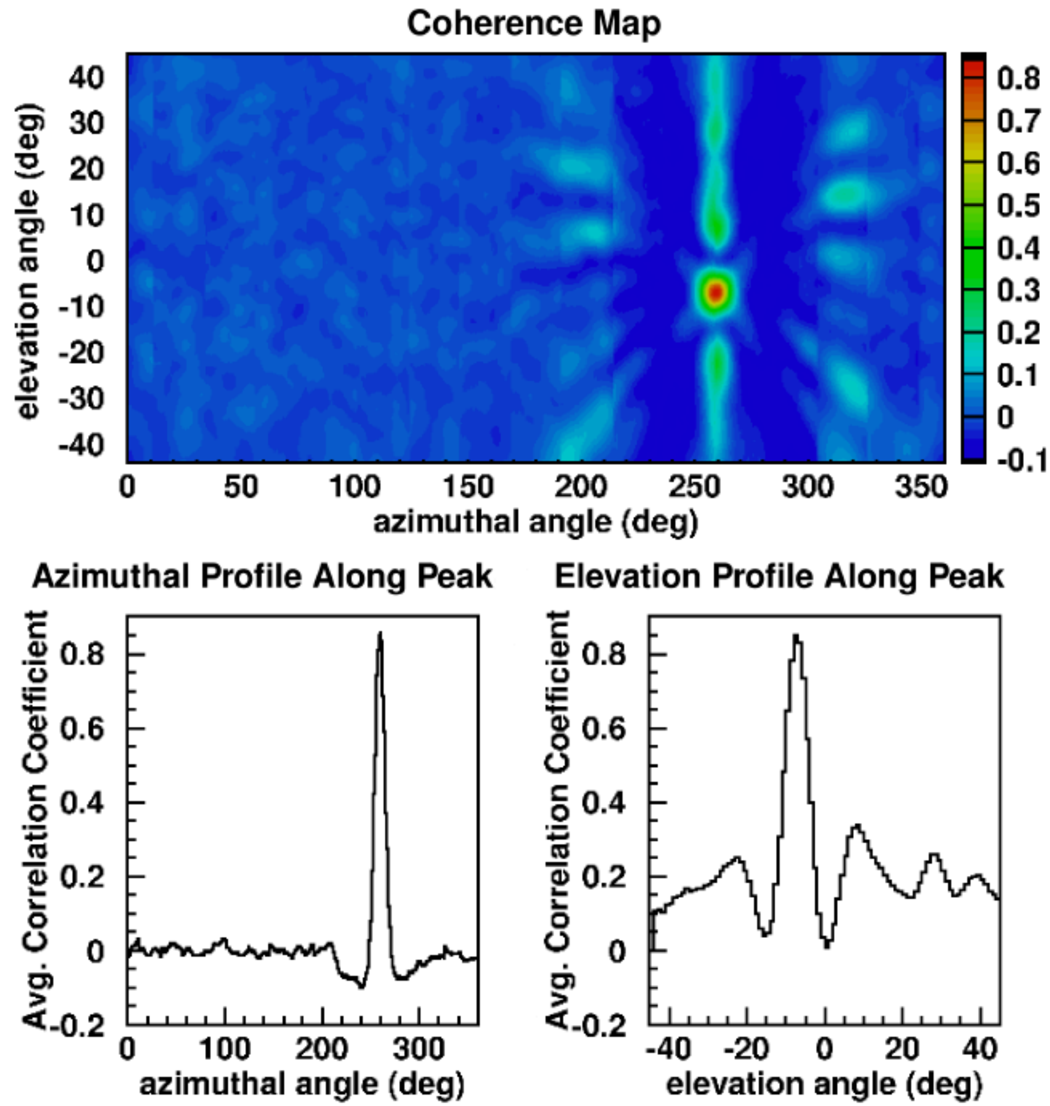
Romero-Wolf et al., arXiv:1304.5663

Beam-forming with Cross-correlations

Example of a global coherence map derived from the sum of cross-correlations.

The true direction of the signal presents itself as a sharp peak.

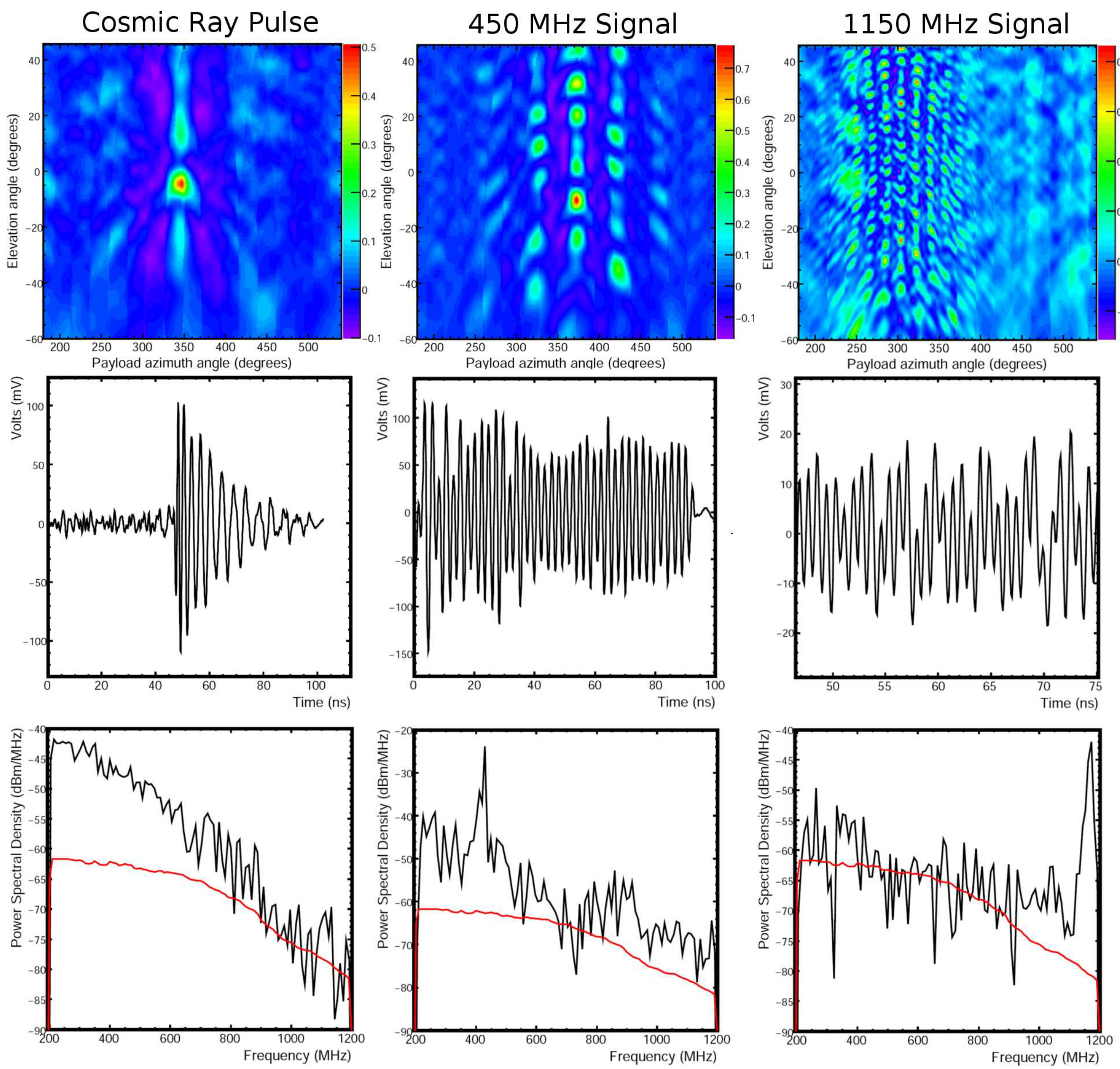
The map is analogous to the dirty map of radio interferometry.



Romero-Wolf et al., arXiv:1304.5663

Beam-forming with Cross-correlations

Examples of signals and backgrounds detected with ANITA.

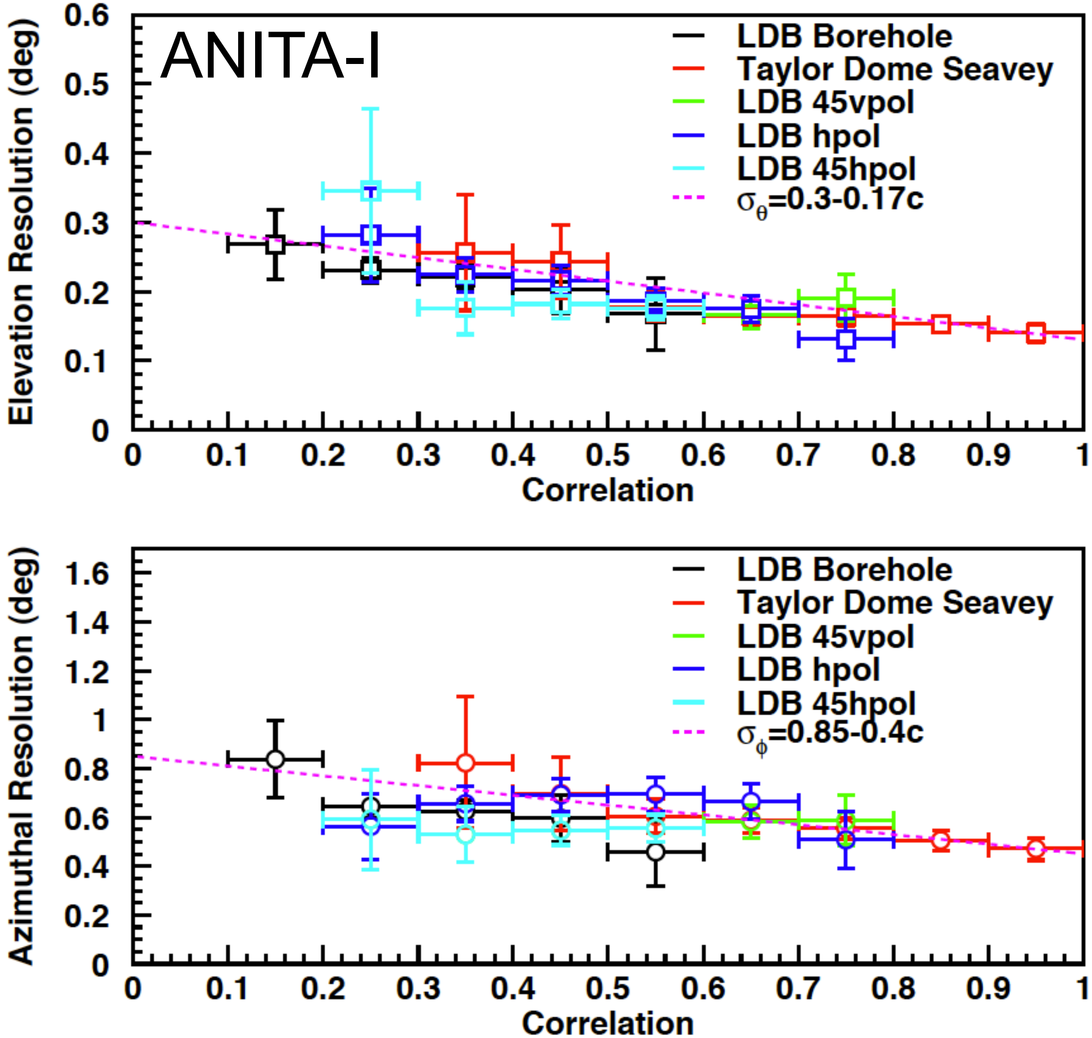


Romero-Wolf et al., arXiv:1304.5663

Angular Error

The ANITA array has < 1-degree angular errors.

This is due to the ultra-wideband signals used in the correlation.



Romero-Wolf, PhD Thesis

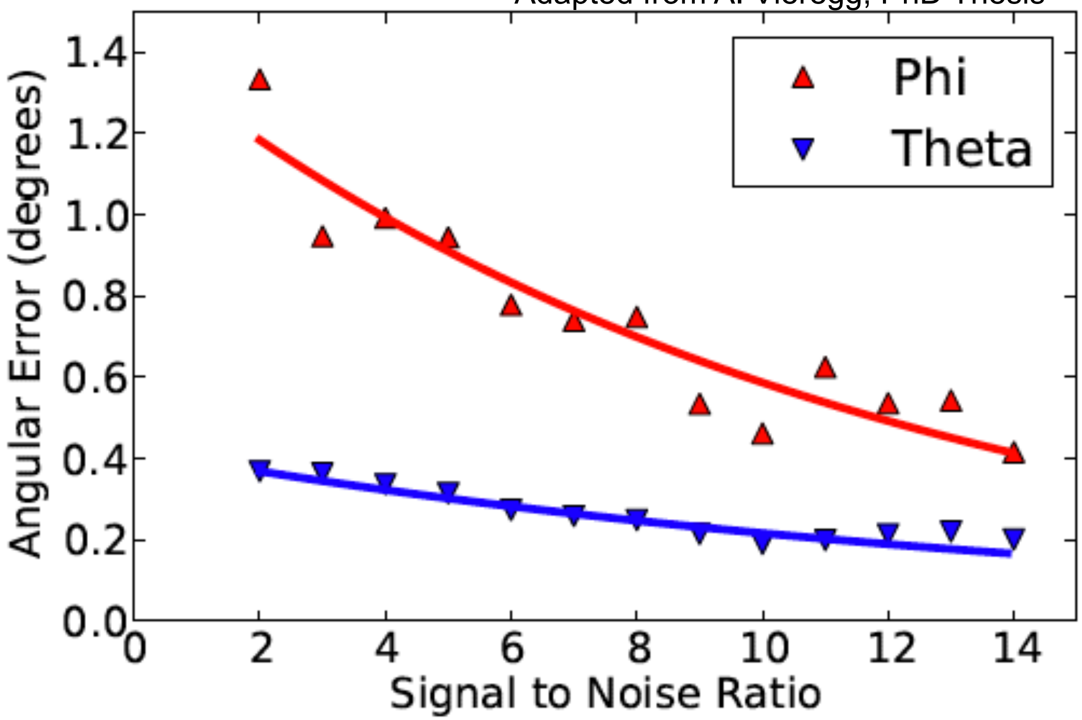
Angular Error

The ANITA array has < 1-degree angular errors.

This is due to the ultra-wideband signals used in the correlation.

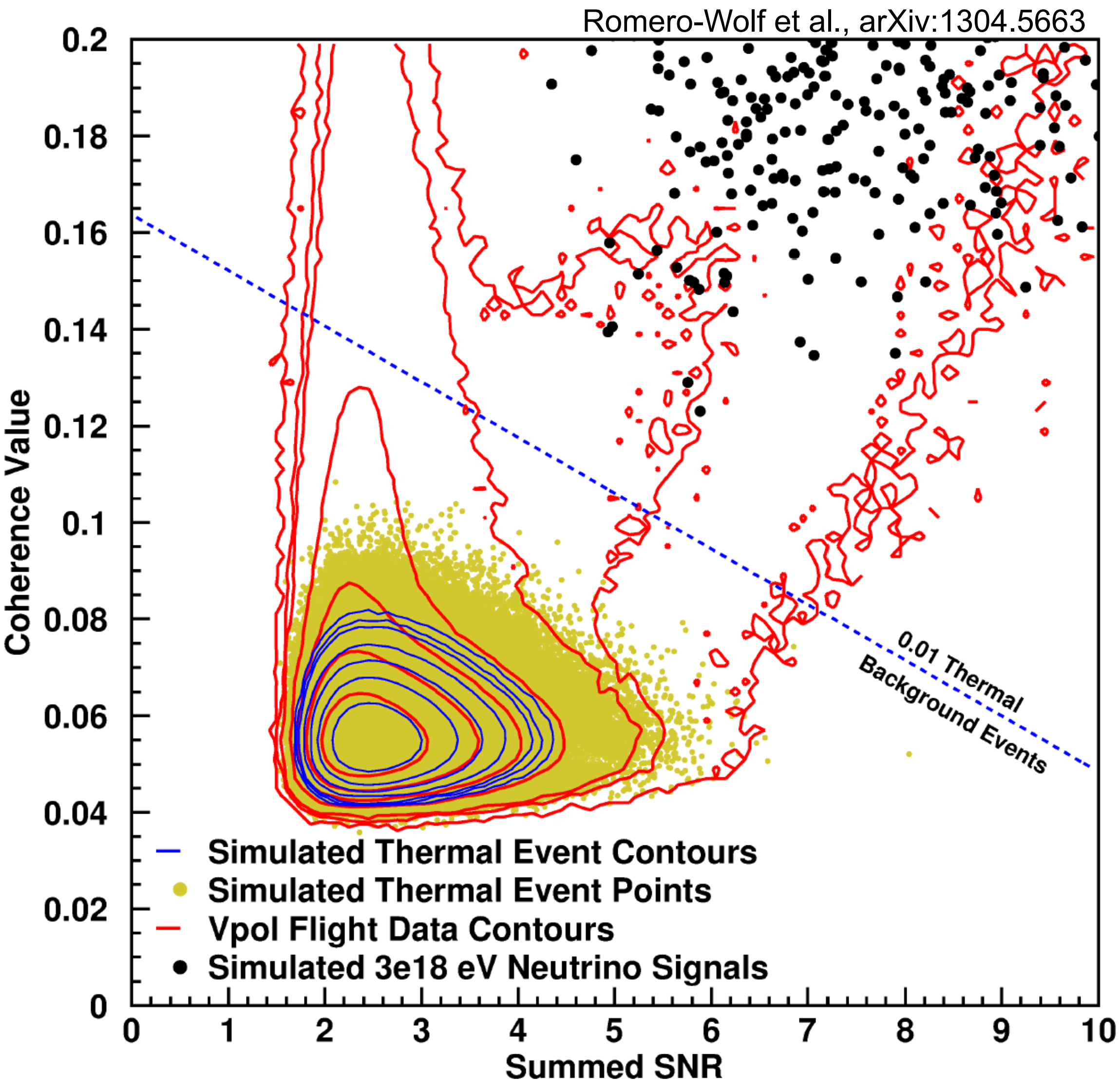
ANITA-II

Adapted from A. Vieregg, PhD Thesis



Summed Waveforms vs. Cross-Correlations

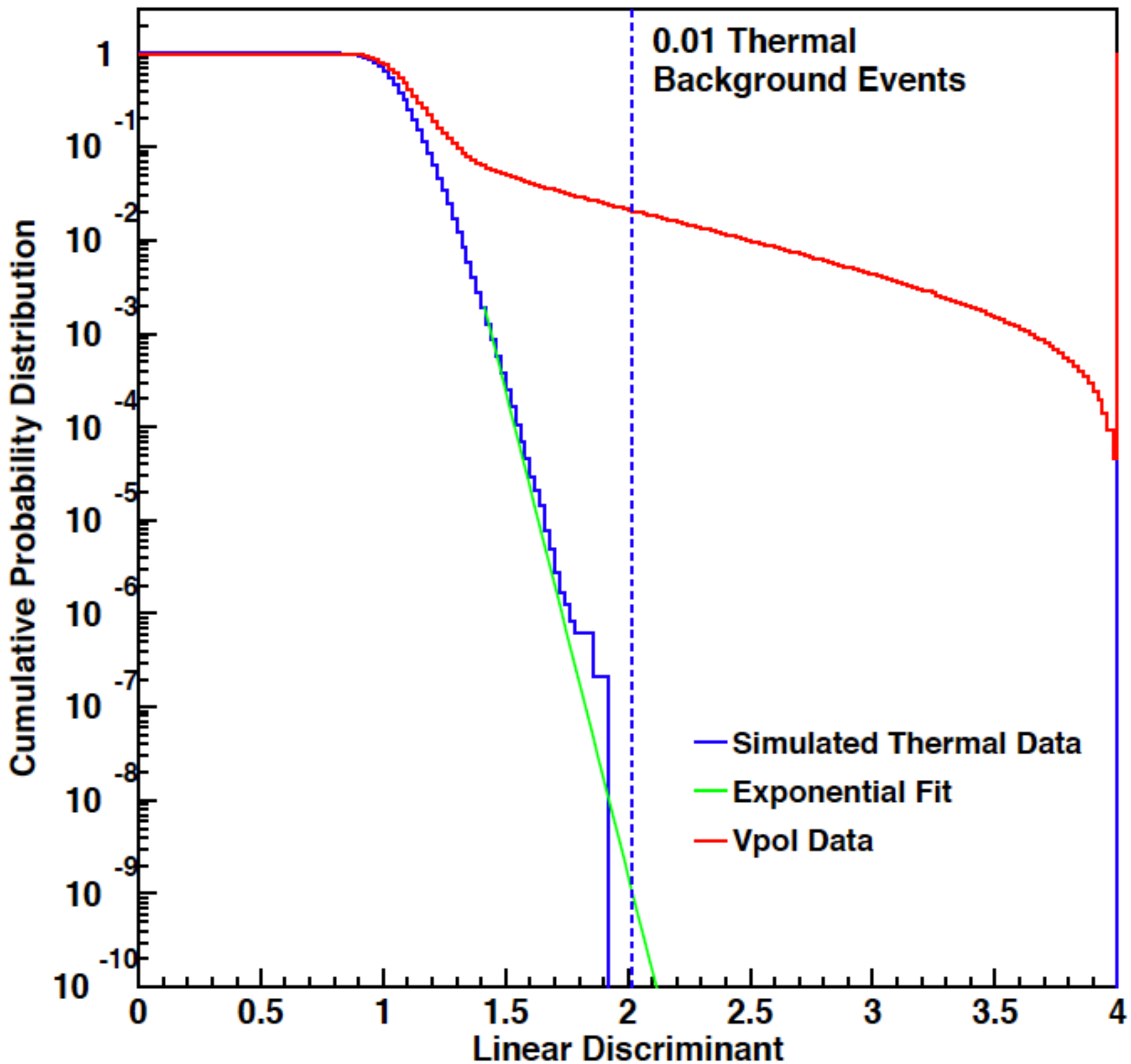
The relation between the summed waveform signal to noise ratio and cross-correlation coefficient reveals features that are specific to each kind of signal and background.



Thermal Noise Rejection

Romero-Wolf et al., arXiv:1304.5663

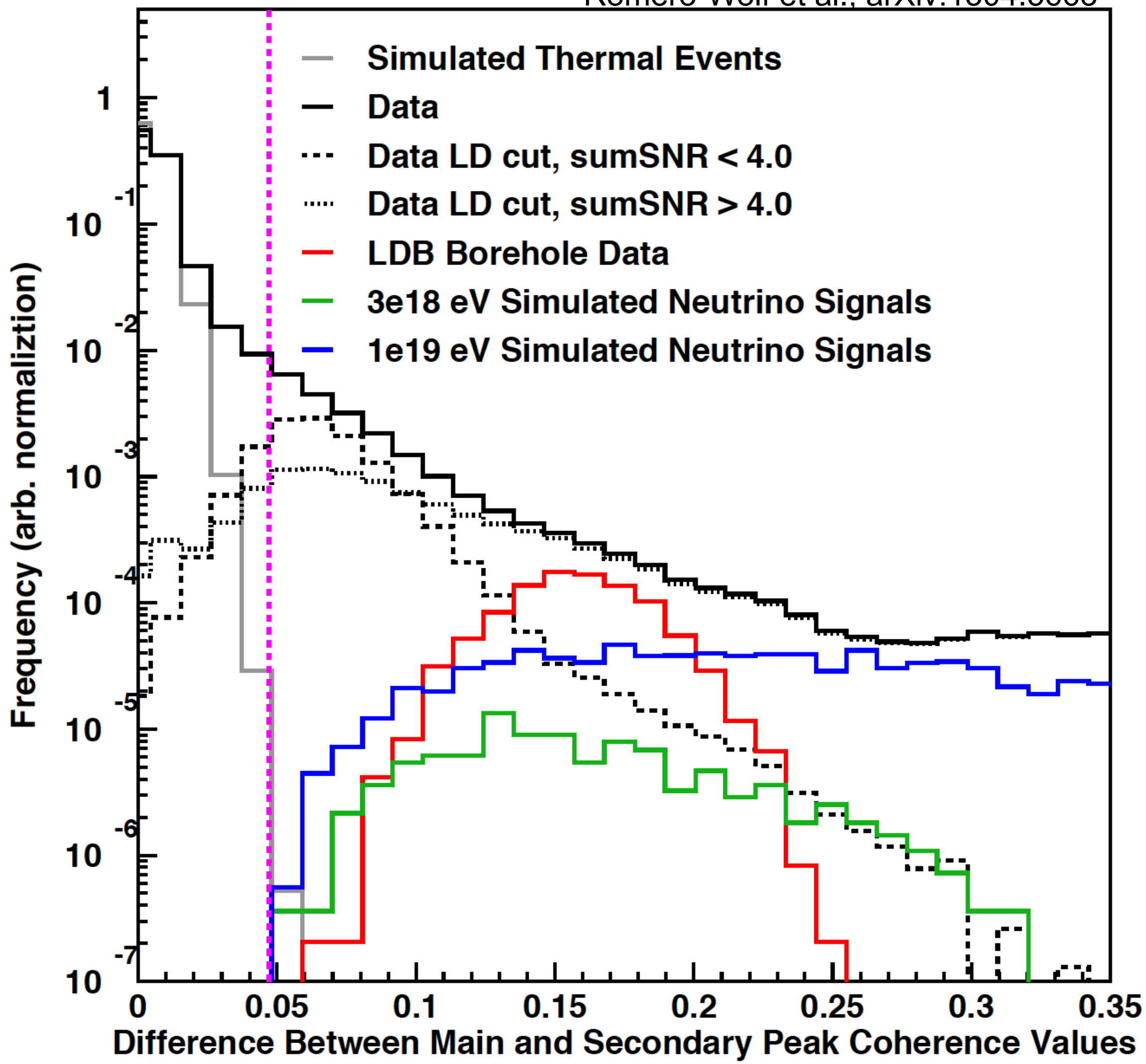
A discriminant formed by the linear combination of the cross correlation coefficient and the peak of the summed waveform provides a highly efficient filter.



Discrimination Techniques

Thermal noise and carrier wave signal backgrounds both have comparable peak and secondary lobes.

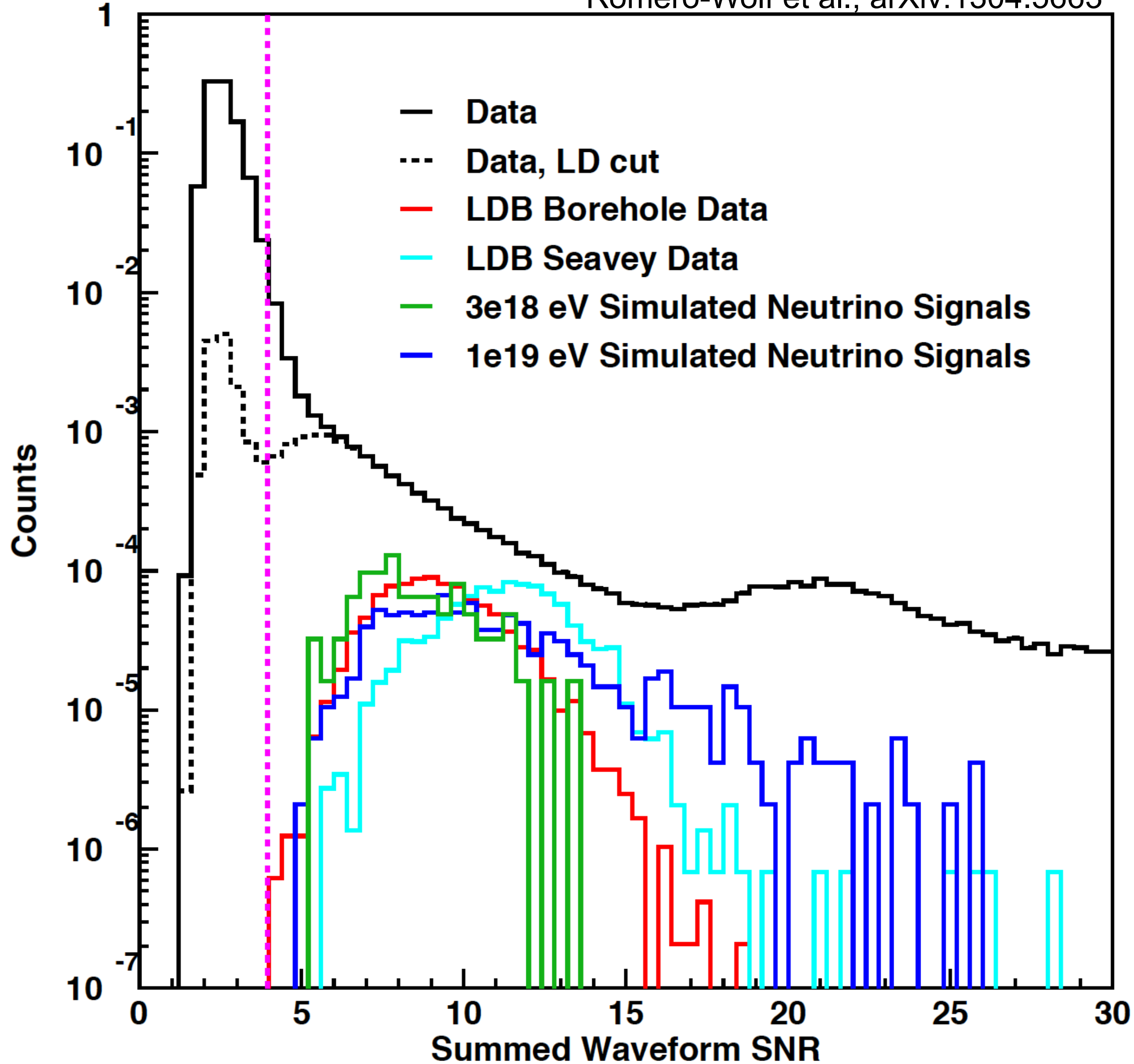
Romero-Wolf et al., arXiv:1304.5663



Signal Strength

The peak of the coherent waveform sum provides additional efficient discrimination between signals of interest and thermal noise.

Romero-Wolf et al., arXiv:1304.5663

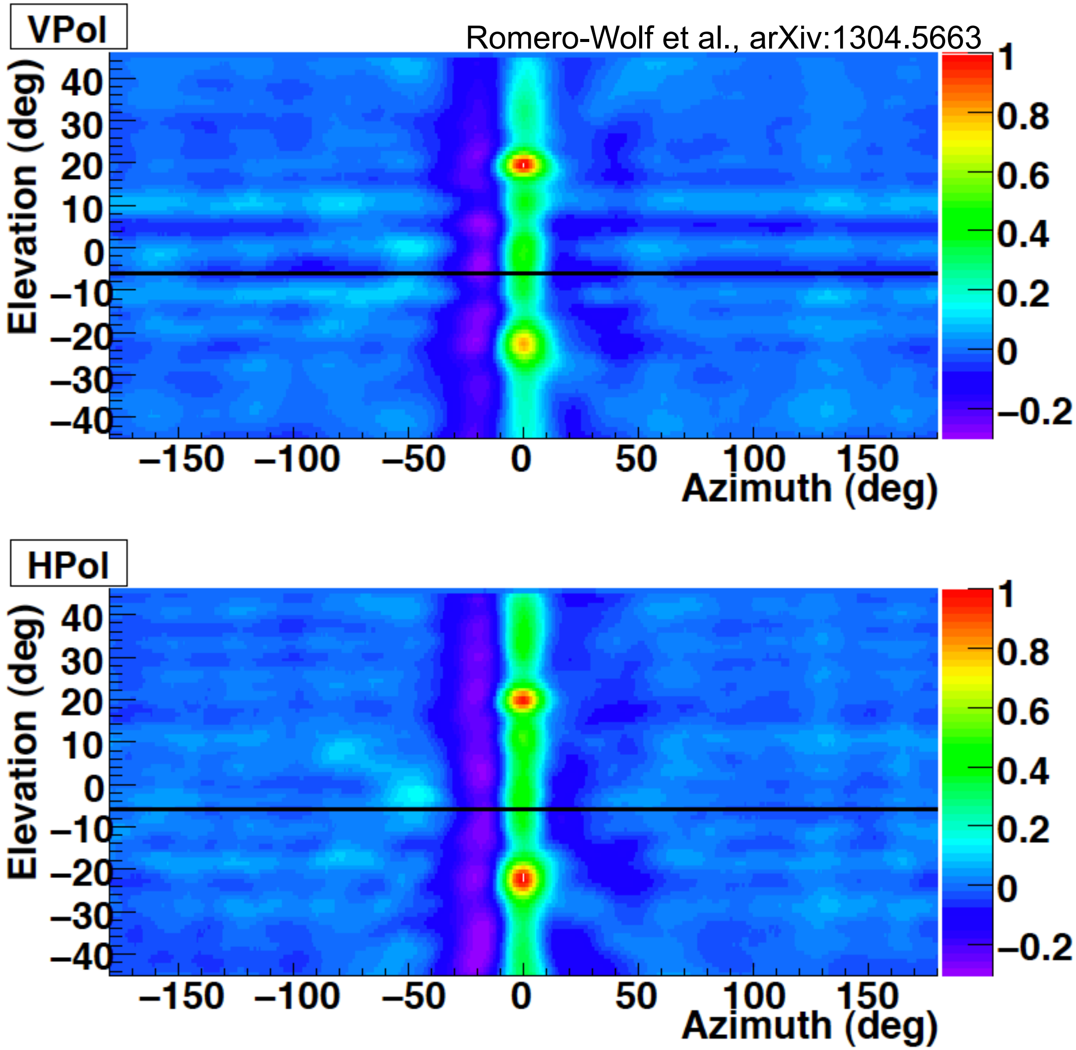


Imaging the Sun

Averaging events in a sun-centered coordinate system reveals a radio image of the sun along with its reflection on the ice.

These images can be used to measure the surface roughness of the ice.

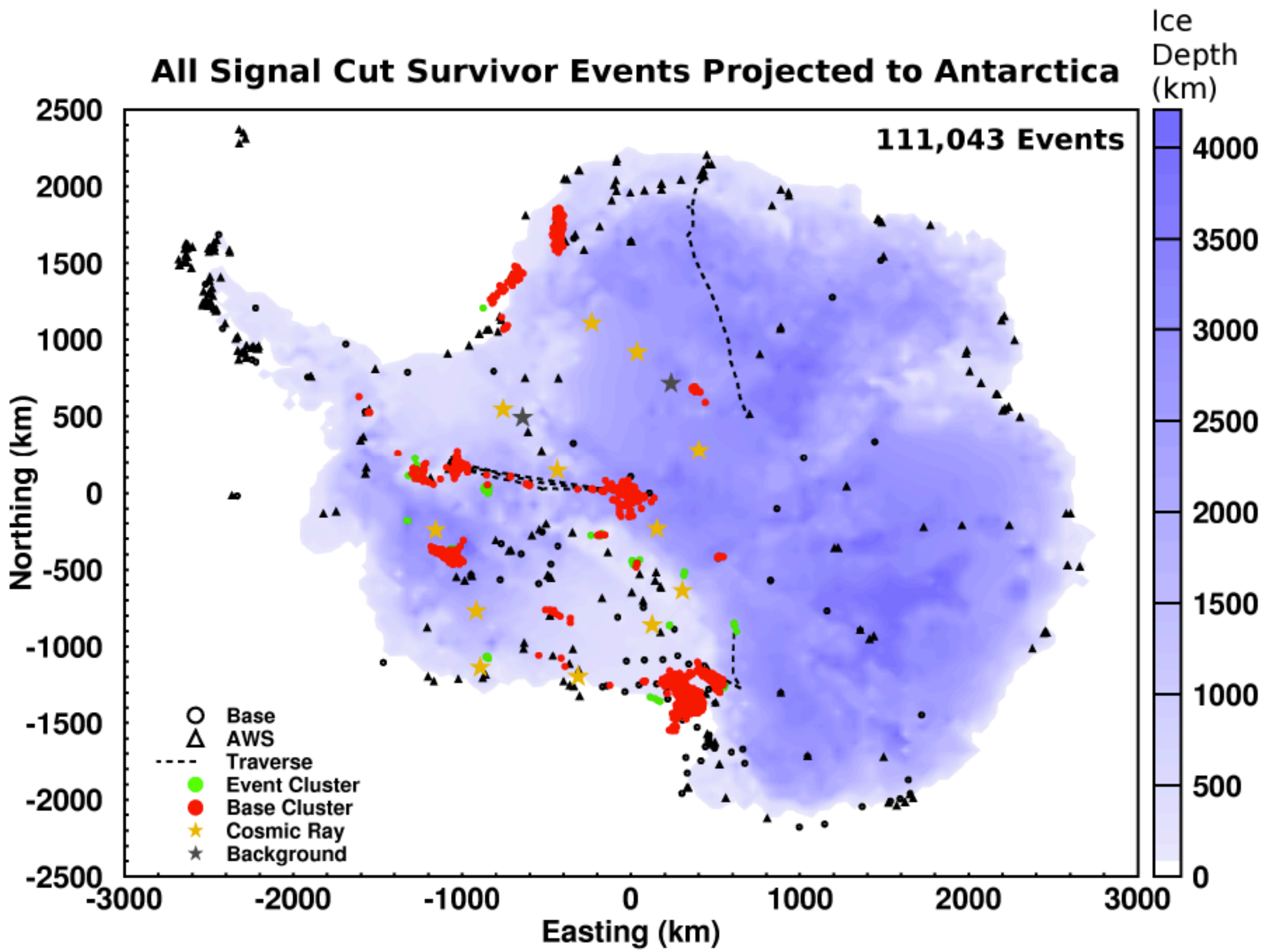
S. Hoover, PhD thesis
Besson et al., arXiv:1301.4423



Imaging Anthropogenic Backgrounds

Clusters of events that pass all cuts provide locations of anthropogenic backgrounds.

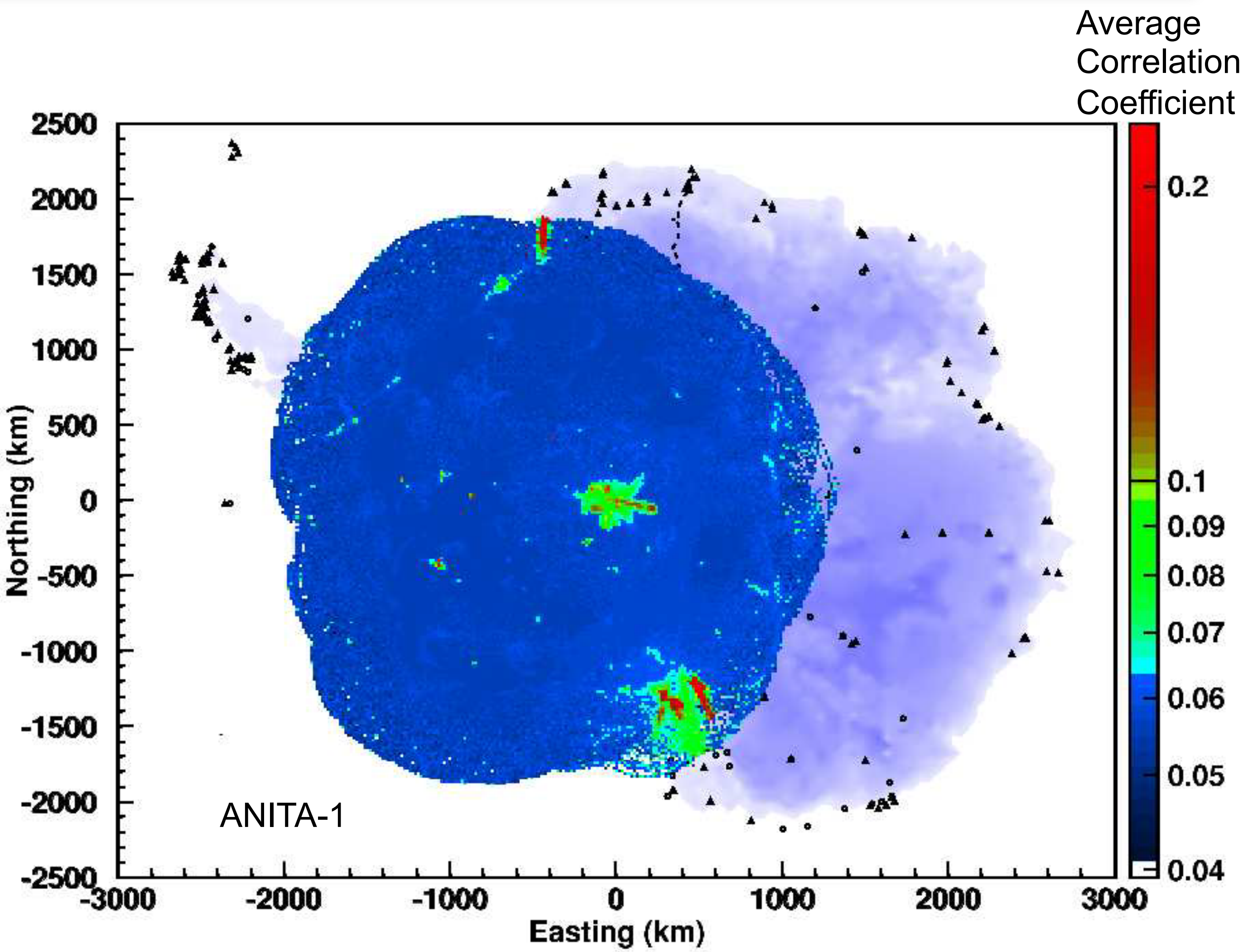
Not all clusters originate from identified field camps.



Romero-Wolf, PhD Thesis

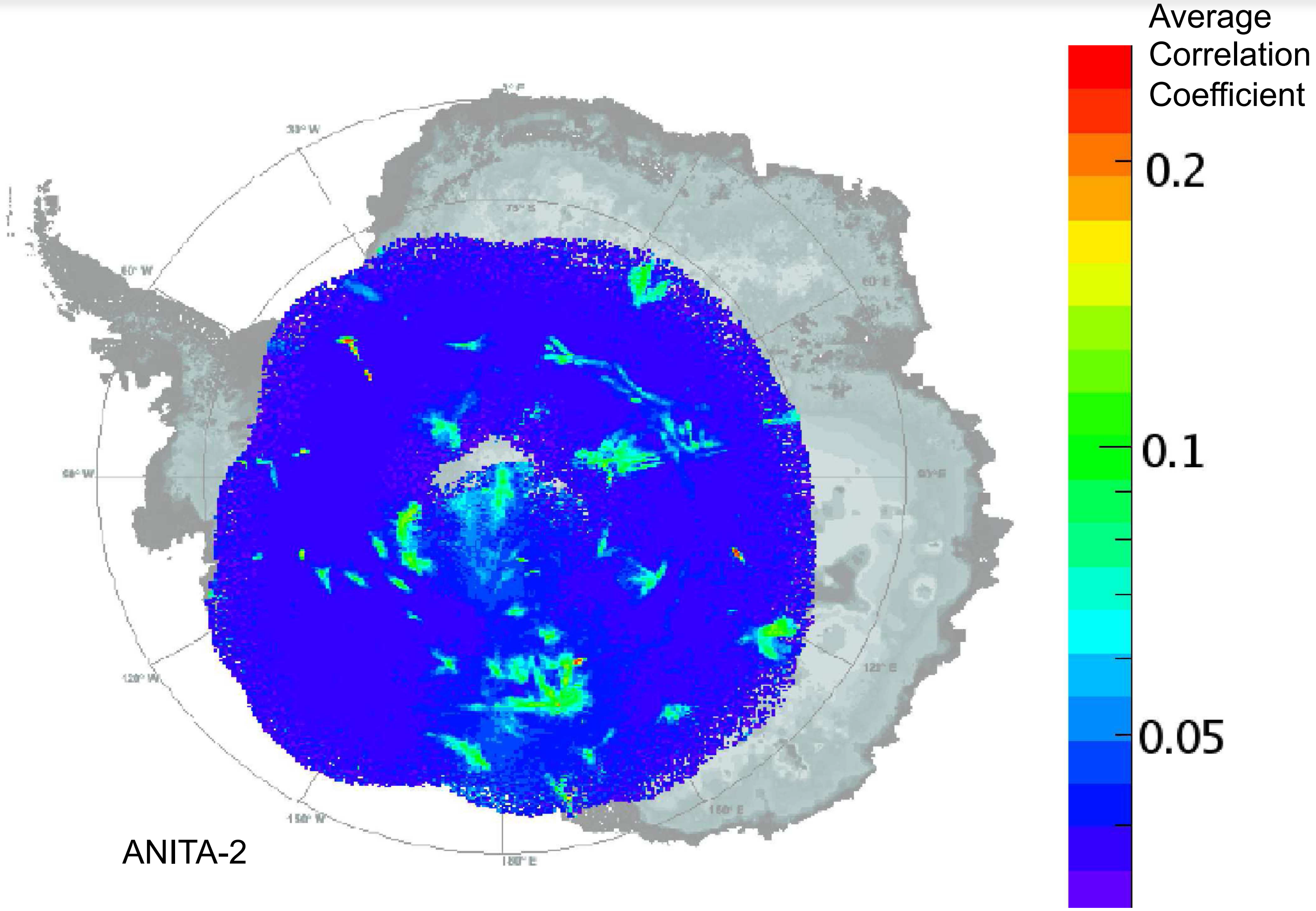
Imaging Anthropogenic Backgrounds

Imaging of all data, including thermal noise, provides a complementary view of the Antarctic noise sources.



Romero-Wolf et al., arXiv:1304.5663

Imaging Anthropogenic Backgrounds



A. Vieregg, PhD Thesis

A Real-Time Beam Forming Trigger for Radio Detection of Ultra-High Energy Particles

Real-Time Trigger Requirements

This trigger design needs to be a

lean

- At 2.6 Gsa/s, the sample bit resolution needs to be minimized.

mean

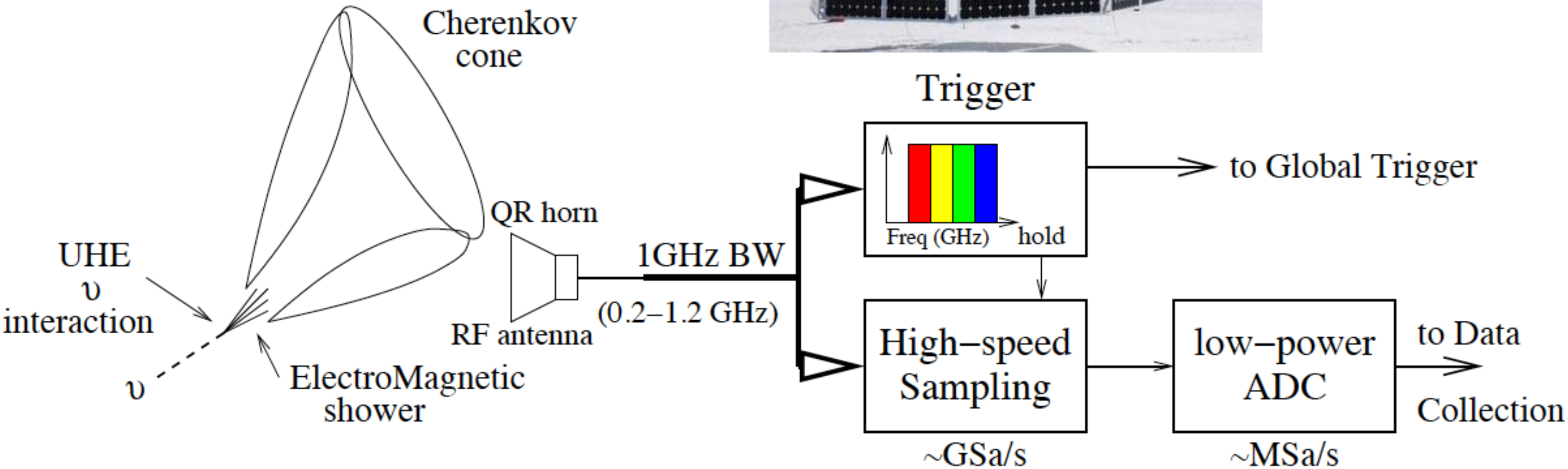
- 96 Channels operating in real-time requires a minimum number of operations to achieve beam-forming.

fighting machine

- This design must outperform the previous ANITA trigger approach.

The ANITA-1 Trigger

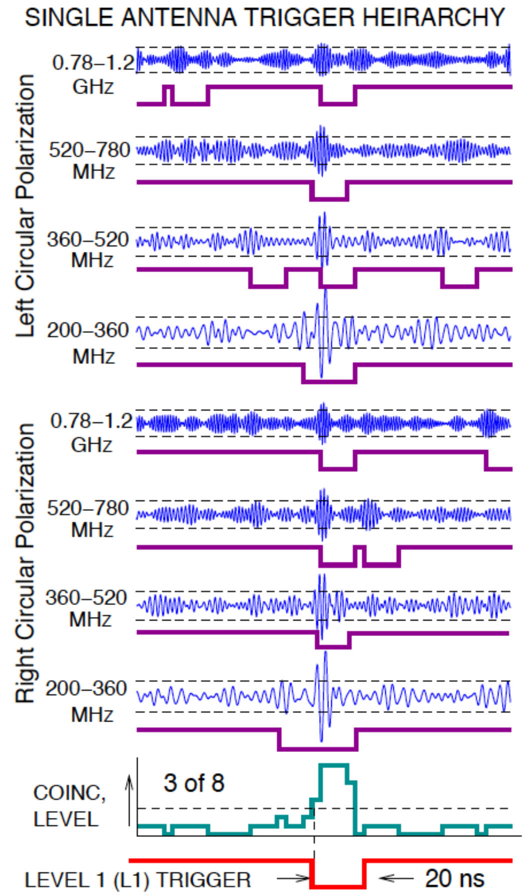
- Dual polarized horns.
- Signals are pre-amplified and fed into instrument box.
- Signal chains split into triggering and digitizing.
- Trigger chain splits signal into bands, sets thresholds, and combines signals between bands and neighboring antennas to make trigger decision.



Gorham et al., Aph, 05, 003, 2009

The ANITA-1 Trigger

Design Drivers	**Implementation**
Low power	Tunnel diode and threshold crossing.
Protection against saturation	4 bands per channel Require equal threshold Tunable threshold.
High sensitivity	2.3σ threshold on each band Require coincidence in bands and neighboring antennas.
Manageable data rate.	Servo thresholds for 5 Hz accidentals trigger rate.
Linearly polarized	Analog rejection of circularly polarized signals using hybrids.



Antenna L1 trigger checks for coincidence with adjacent antennas to make final trigger decision.

Gorham et al., Aph, 05, 003, 2009

The ANITA-2 Trigger

Azimuthal masking: better solution against blasting anthropogenic backgrounds.

New band scheme improved efficiency (50% efficient at 3.3σ SNR).

28.5 days live time in a 31 day flight.

Added 8 antennas + new trigger and better flight path gave a factor of 2.5 improvement over ANITA-1.

Still no neutrinos…
Shot ourselves in the foot on cosmic rays…

Design Drivers	**Implementation**
Low power	Use tunnel diode detectors.
Protection against saturation	Mask payload direction where excessive triggering occurs.
High sensitivity	3 sub-bands + 1 full band. Always require full band and 2 out of the 3 sub-bands. Trigger on Vpol only.
Manageable data rate.	Servo thresholds for 10 Hz accidentals trigger rate.
Linearly polarized	Vpol only. Go for broke on neutrinos.

The ANITA-3 (Tunnel Diode) Trigger

Azimuthal masking: better solution against blasting anthropogenic backgrounds.

New band scheme improved efficiency (50% efficient at 2.9σ SNR).

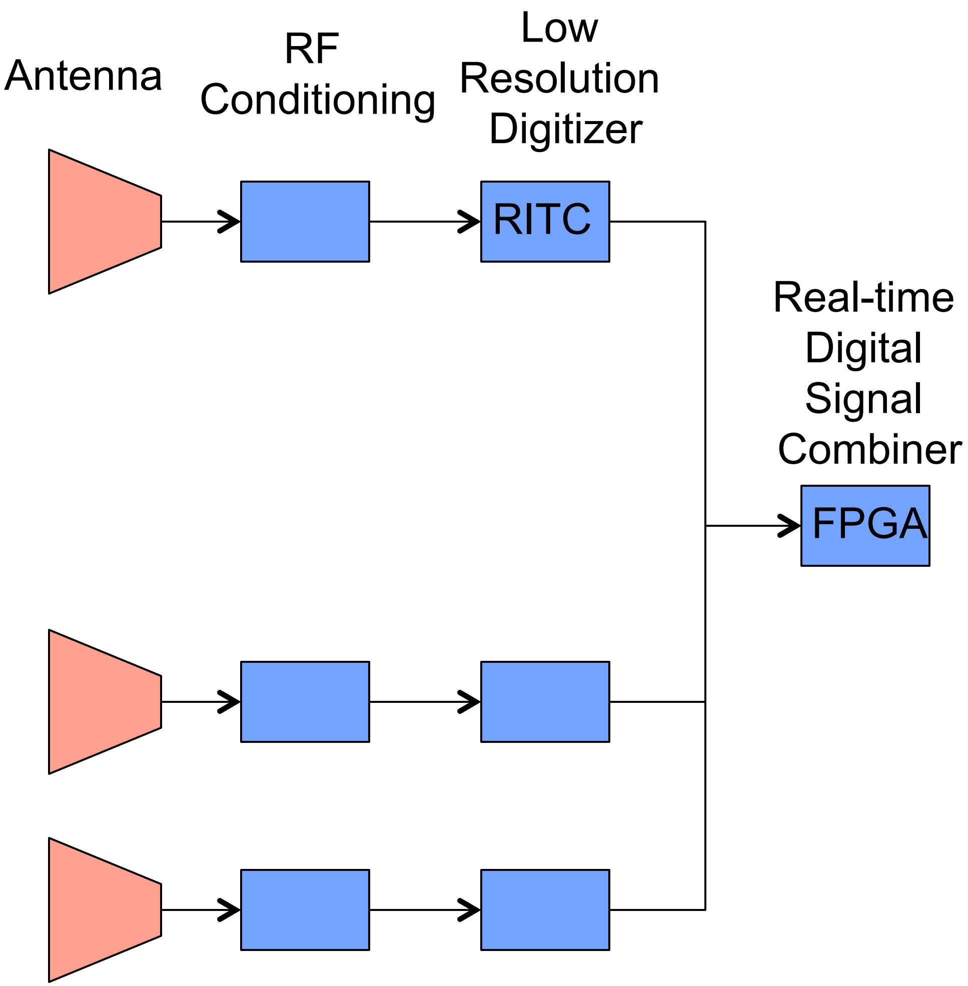
Added full ring of antennas.

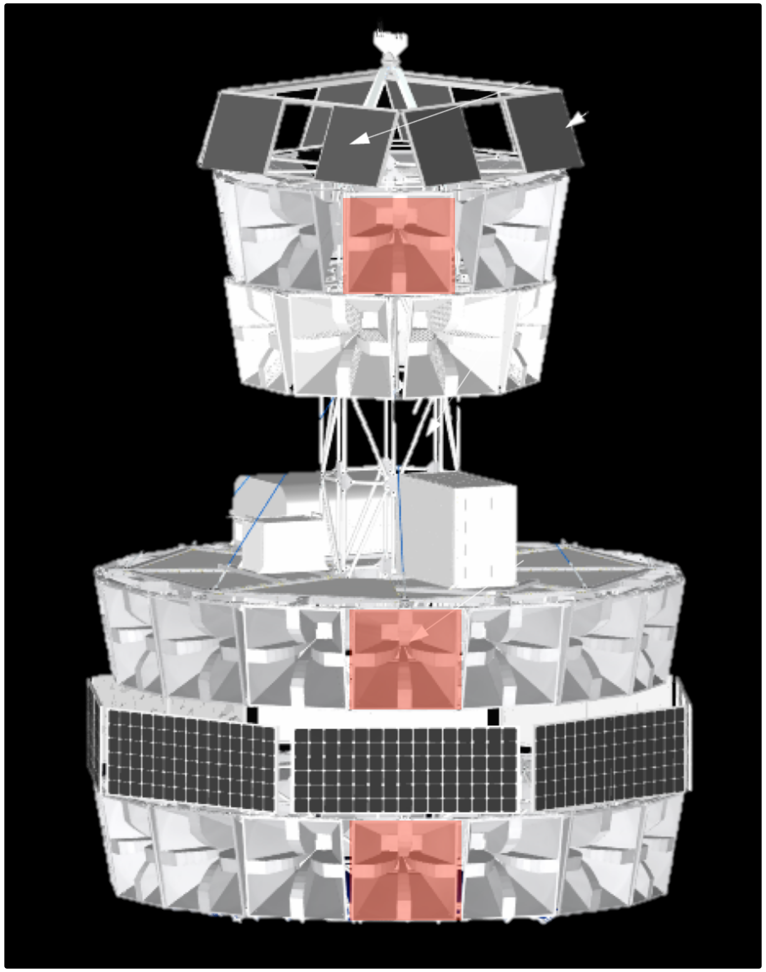
Design Drivers	**Implementation**
Low power	Use tunnel diode detectors.
Protection against saturation	Mask payload direction where excessive triggering occurs.
High sensitivity	Full-band trigger only.
Manageable data rate.	Servo thresholds for 100 Hz accidentals trigger rate. Plans to add GPU for increasing trigger threshold to 1 kHz
Linearly polarized	Vpol and Hpol trigger independently.

ANITA-3 Tunnel Diode Simulations Results

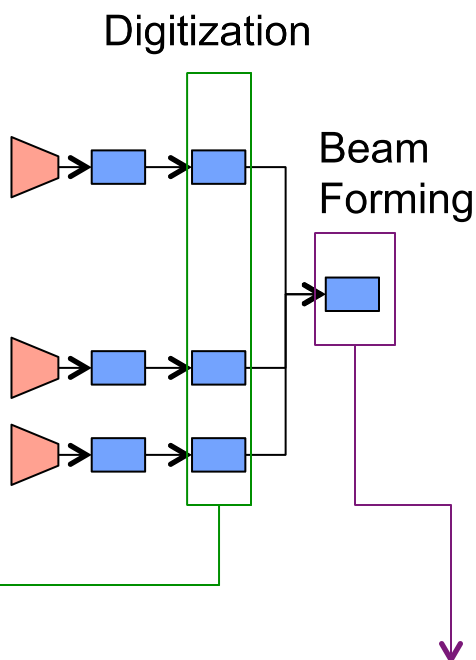
Flight	Laboratory Estimated Performance 50% Eff. SNR
ANITA-1	5.4 (measured)
ANITA-2	3.3 (measured)
ANITA-3 (Tunnel diode)	2.9 (expected)
ANITA-3 (Beam-forming)	2.3 (expected)

General Approach to Designing a Real-time Beam-forming Trigger



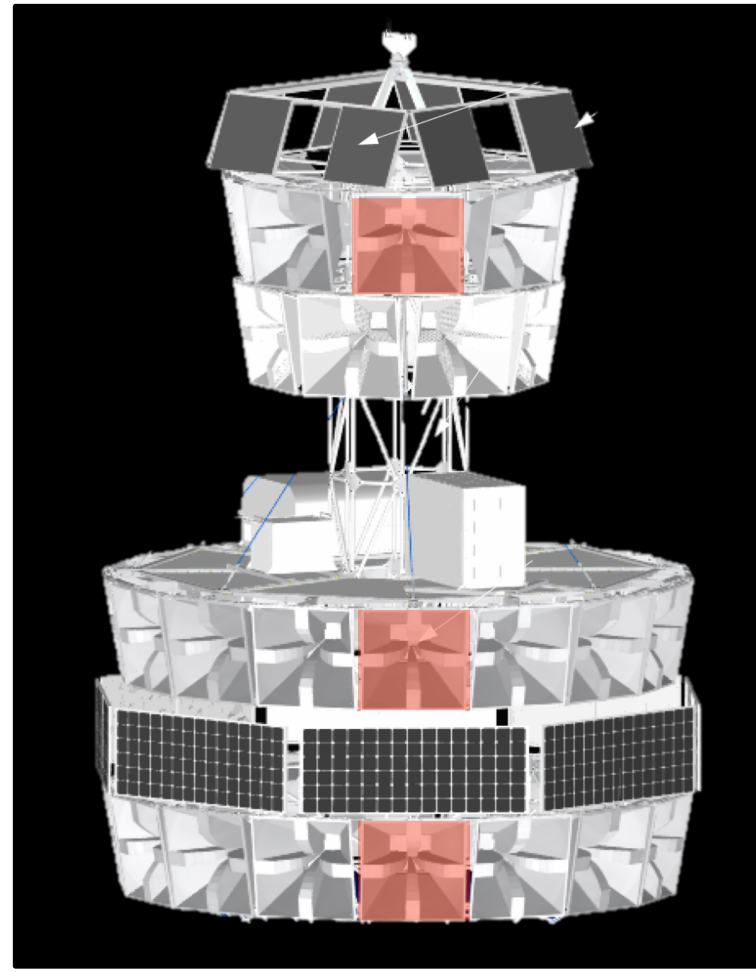


General Approach to Designing a Real-time Beam-forming Trigger

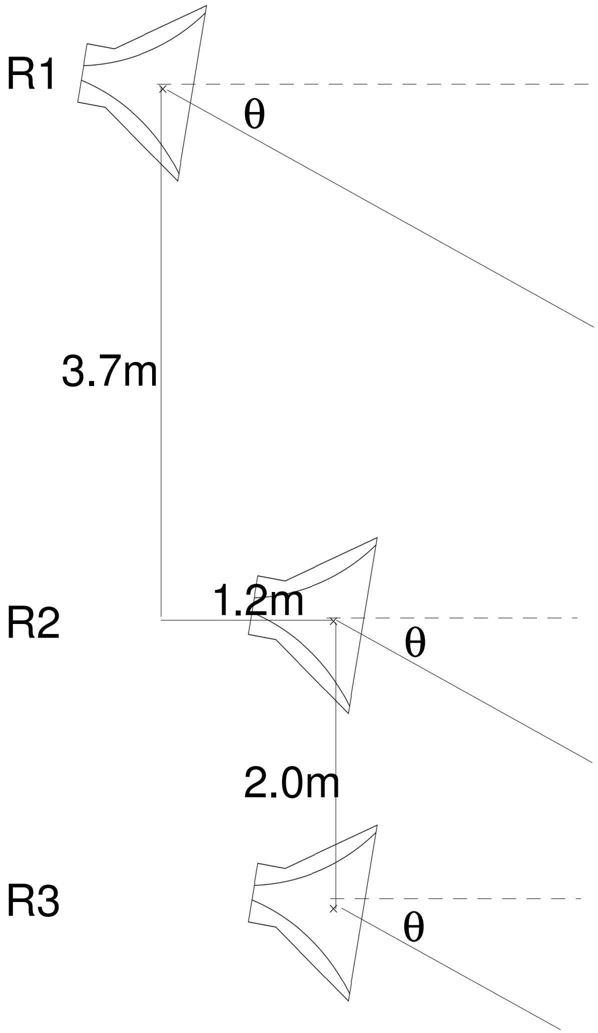


Digitization parameters
- Number of bits
- Step size (in units of noise RMS σ)

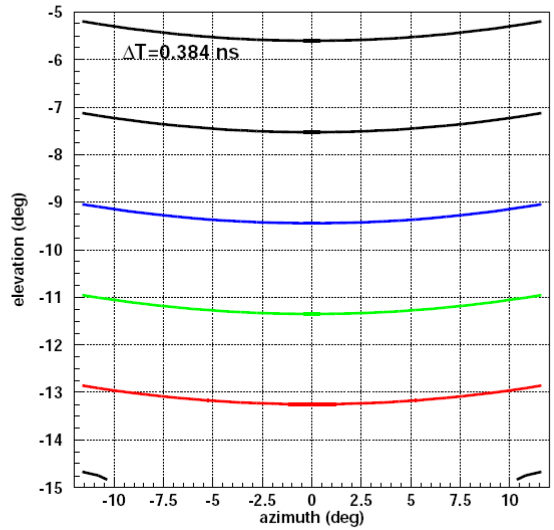
Beam-forming parameters
- Integration time window
- Number of arrival directions tested.



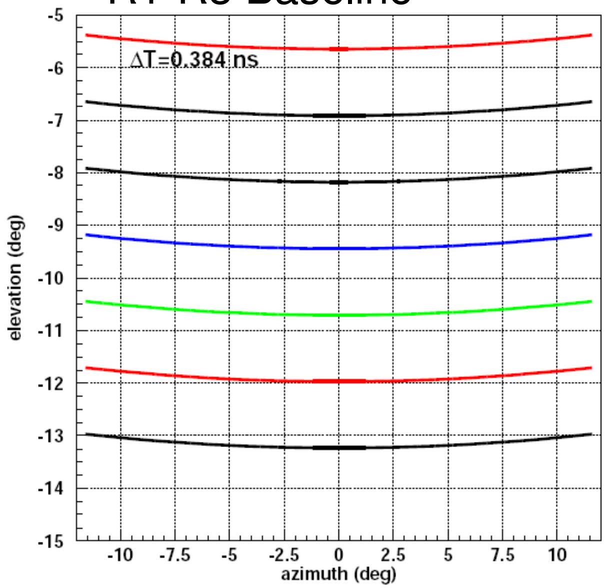
ANITA-3 Phi Sector Geometry



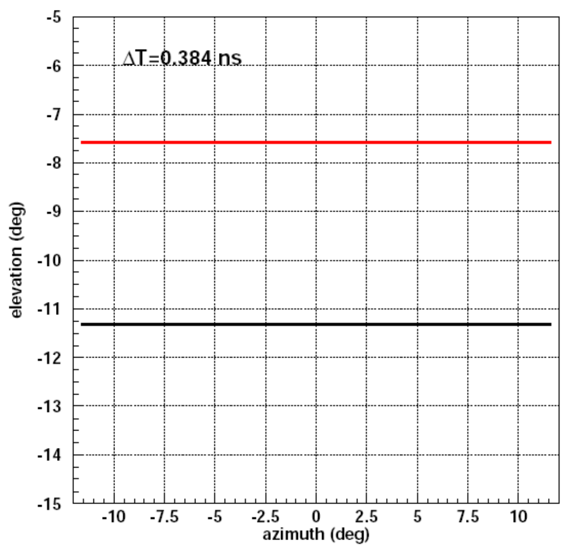
R1-R2 Baseline



R1-R3 Baseline



R2-R3 Baseline



$\Delta\theta$ with ΔT=0.384ns

R1-R2: 2.0°

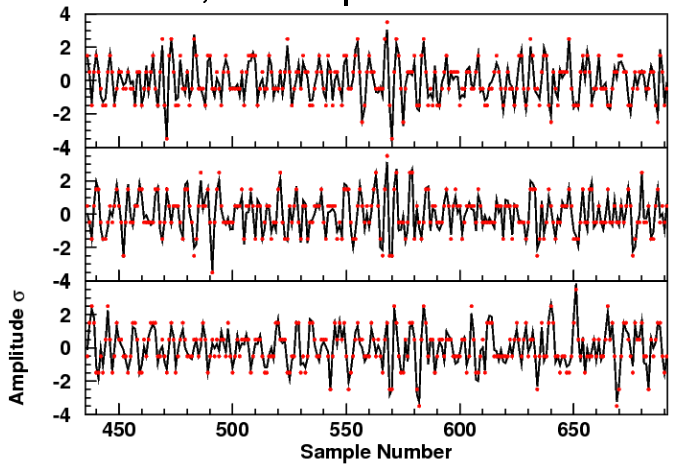
R2-R3: 3.9°

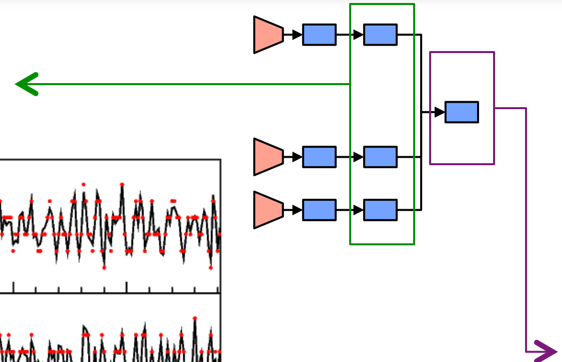
R1-R3: 1.2°

Digitization Examples

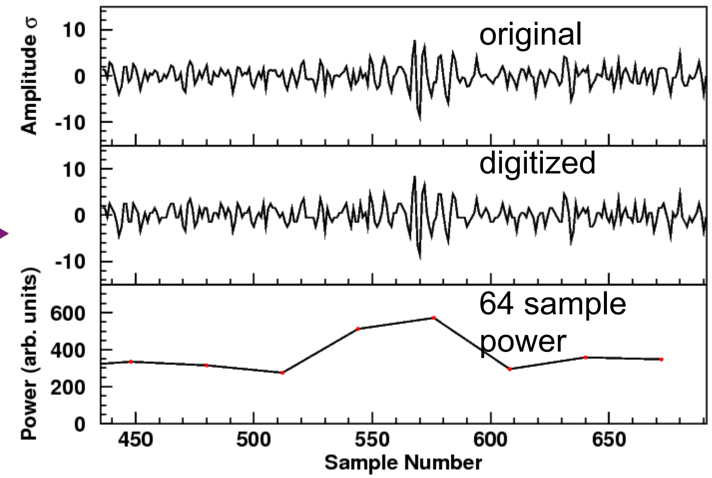
Digitization

3 bits, 1σ steps

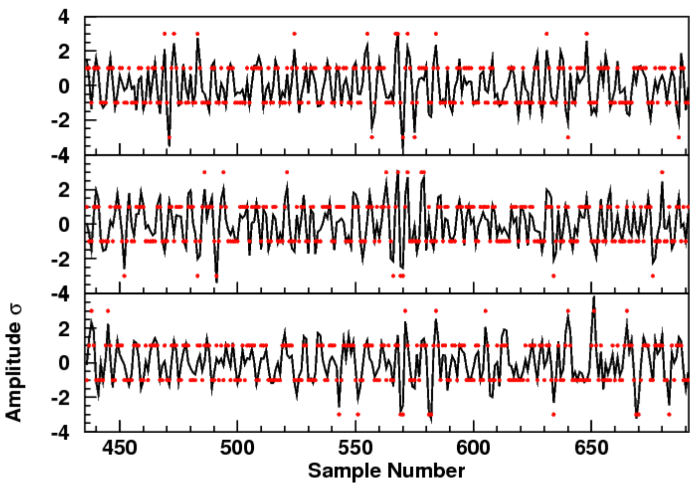


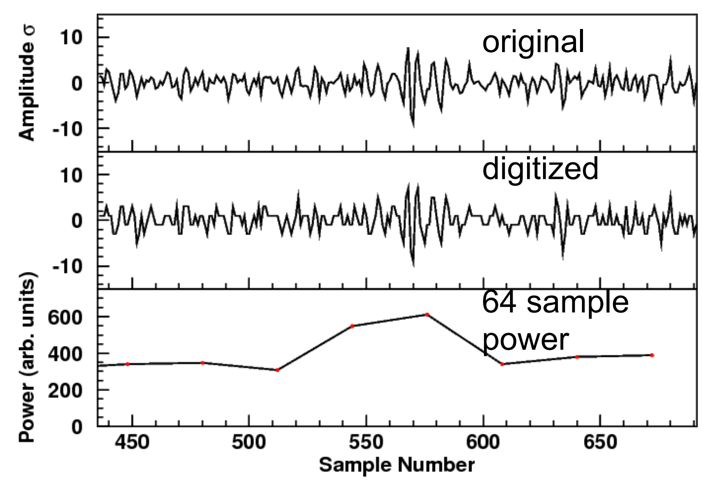


Coherently Summed Waveform



2 bits, 2σ steps





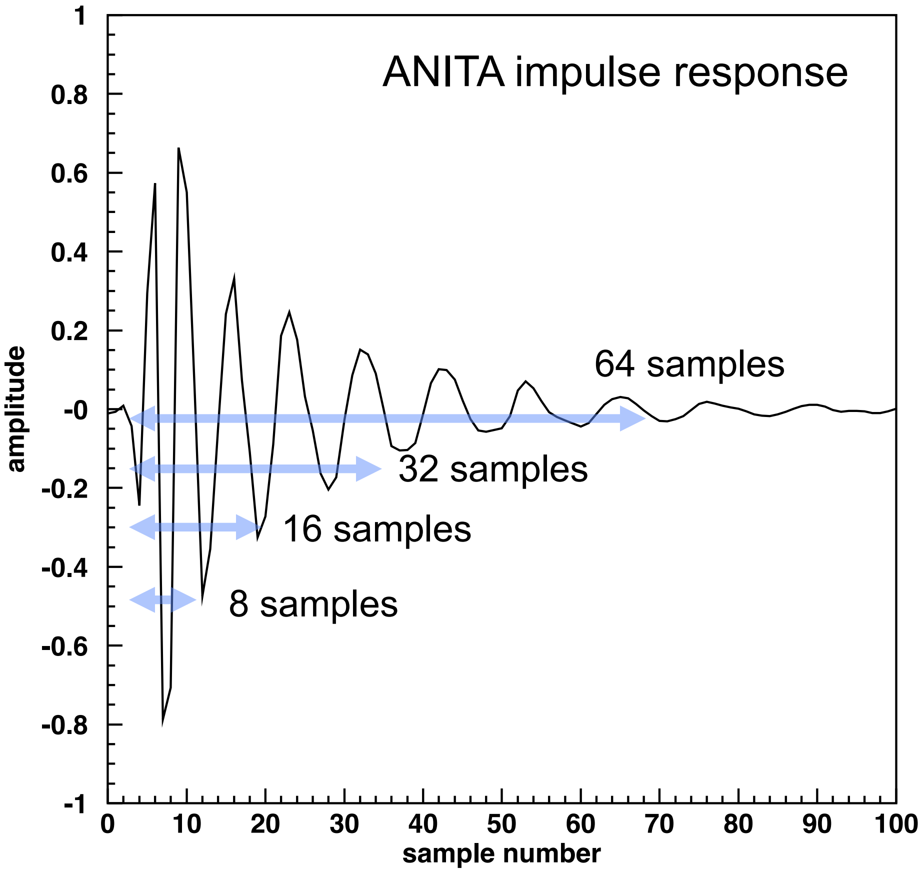
Digitization Variations

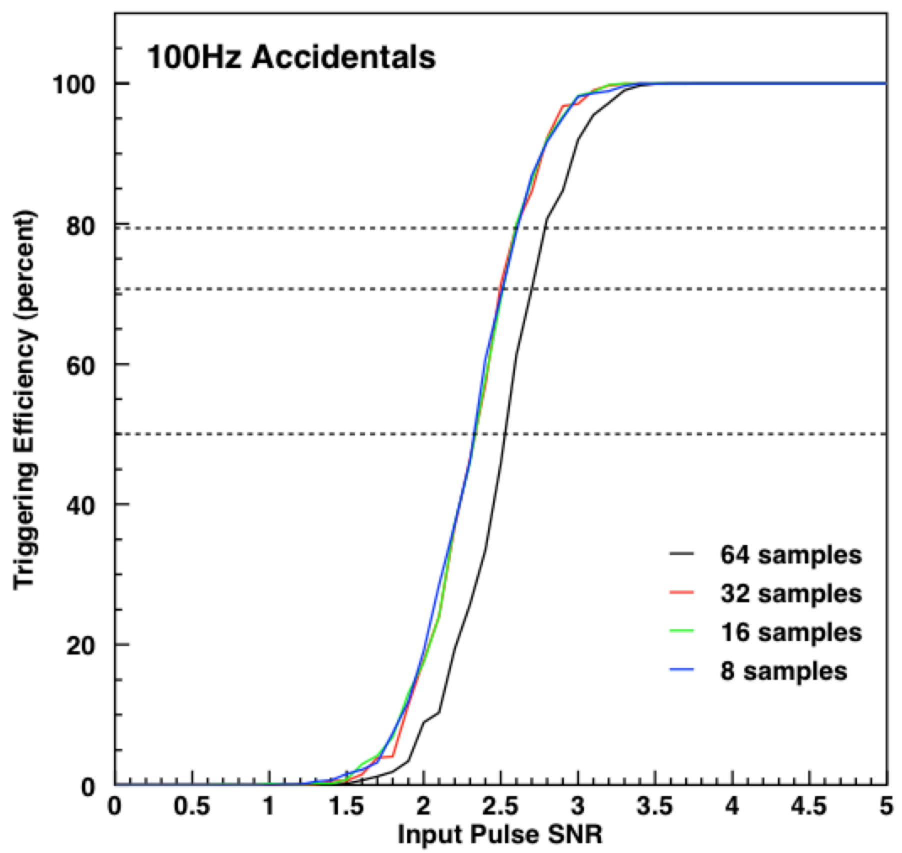
Bits	Levels	Step (σ)	Range (σ)	50% SNR at 10kHz rate
4	16	2.0	+/- 15.0	2.3
4	16	1.0	+/- 7.50	2.15
4	16	0.5	+/- 4.25	2.15
3	8	2.0	+/- 7.00	2.3
3	8	1.0	+/- 3.50	2.15
3	8	0.5	+/- 1.75	2.65
2	4	2.0	+/- 3.00	2.4
2	4	1.0	+/- 1.5	3.0
2	4	0.5	+/- 0.75	4.4

Parameters chosen for earlier studies are optimal.
2-bit digitizers do not look like such a bad alternative if need be.

Integration Time Window

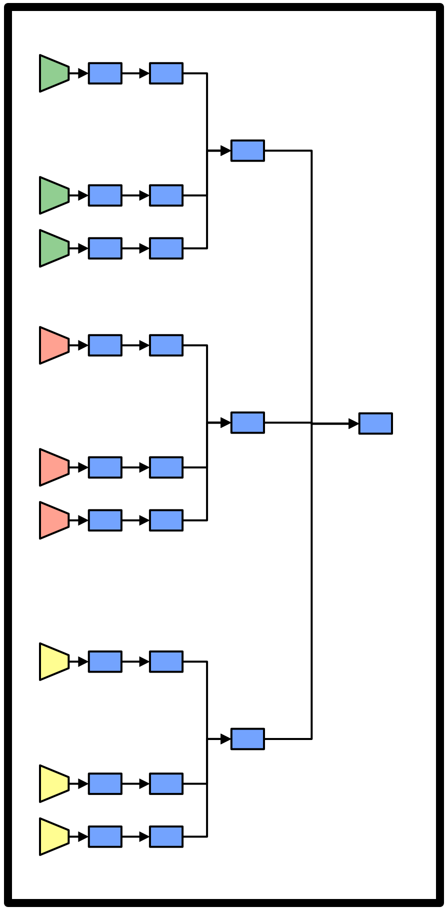
Integrate the power over a given time window W.





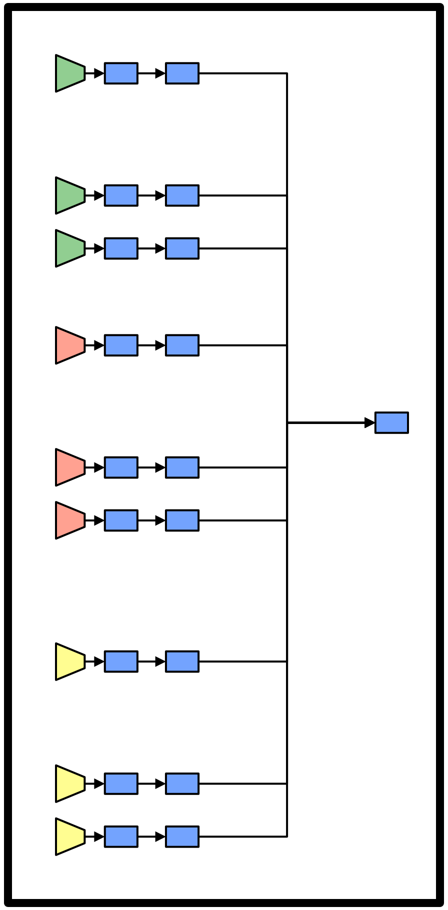
General Approach to Designing a Real-time Beam-forming Trigger

Combine signals in each ϕ-sector, then combine with neighbors

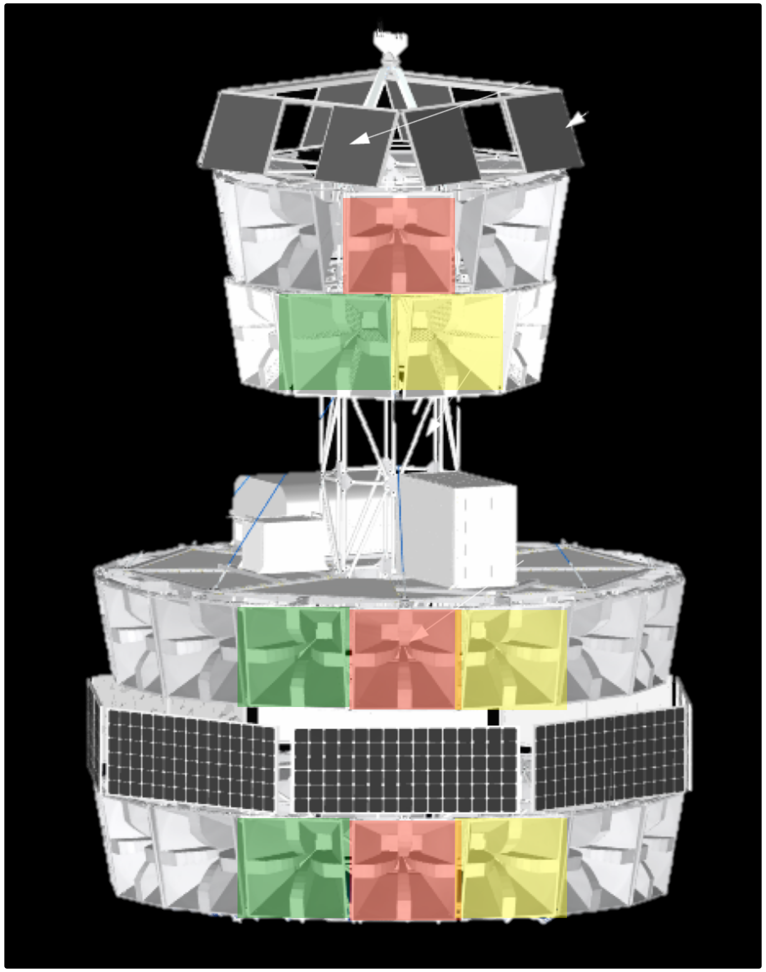


Leaner

Combine all signals from neighboring ϕ-sectors

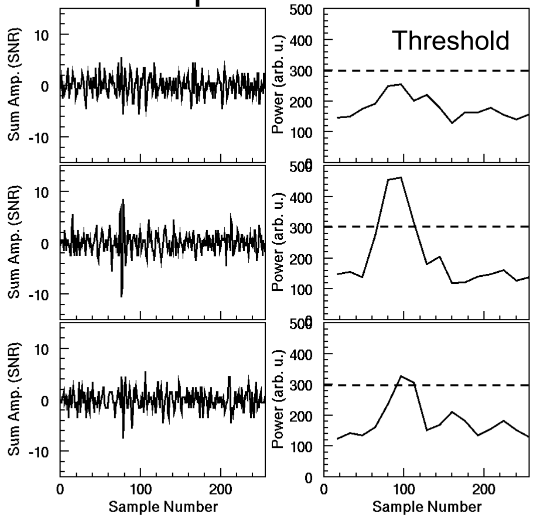


Meaner



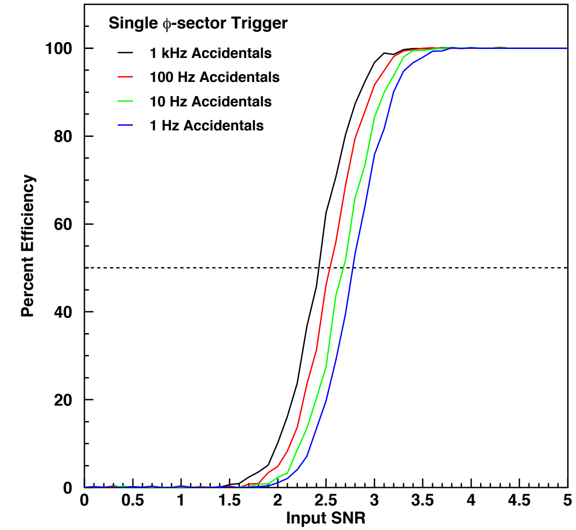
Trigger Efficiencies Using Coincidence Triggers

Technique

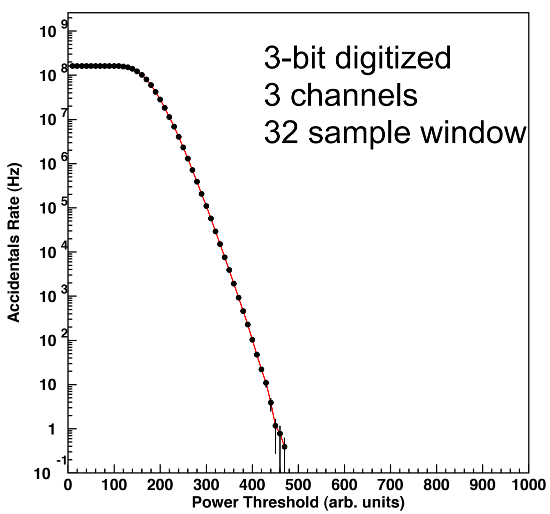


Coincidence requiring 1, 2, or 3 phi-sectors exceed threshold within integration time window.

Efficiency Curves



Thresholds and Accidental Rates



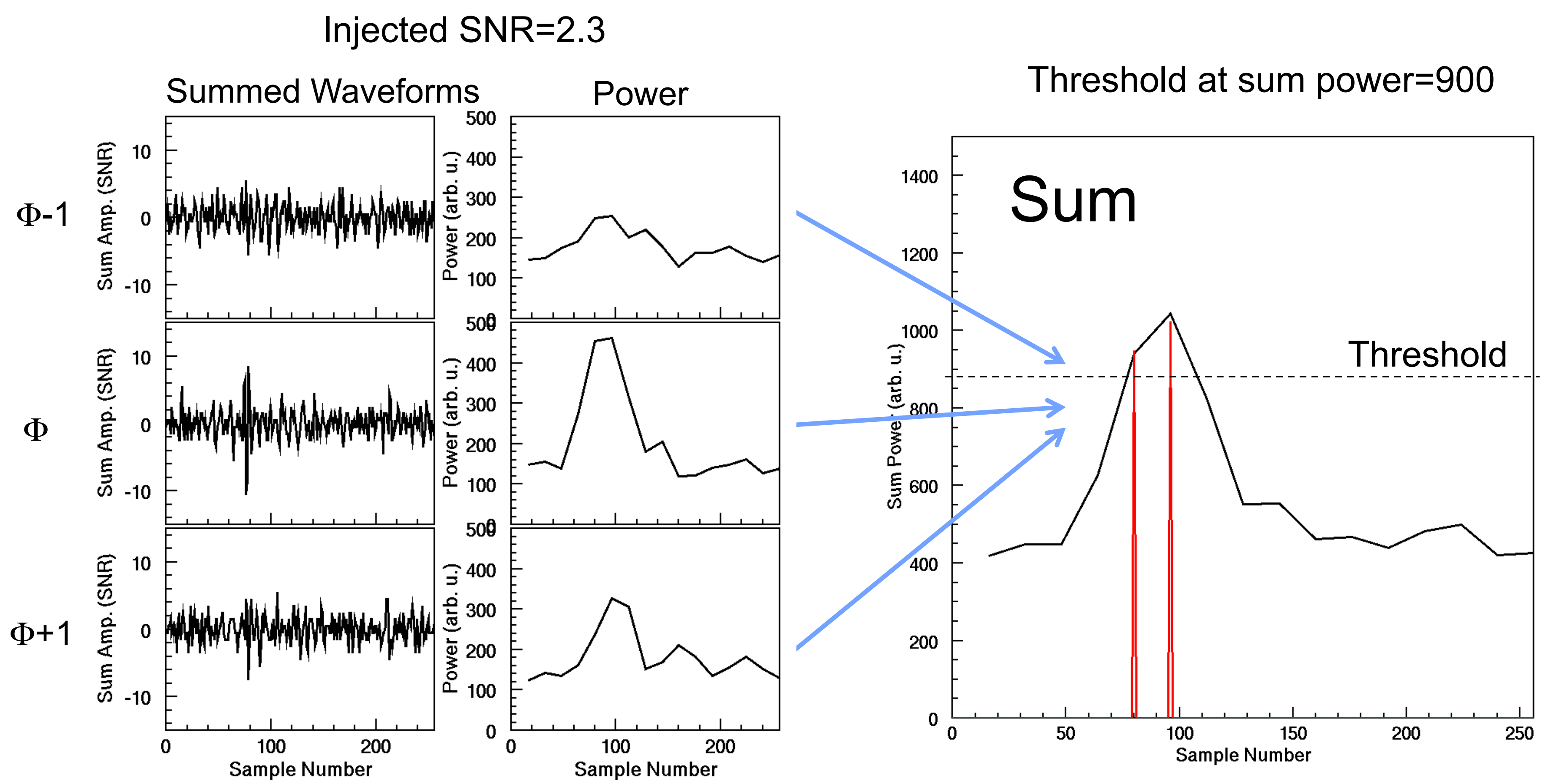
Rate (Hz)	Thresh.
10^7	220
10^6	263
10^5	300
10^4	335
10^3	367
10^2	398
10	428
1	450

Results

Accidentals Rate (Hz)	Any Single ϕ 50% Eff	Double Adjacent 50% Eff	Triple Adjacent 50% Eff
10^3	2.4	2.5	2.6
10^2	2.5	2.6	2.8
10	2.7	2.8	2.9
1	2.8	3.0	3.1

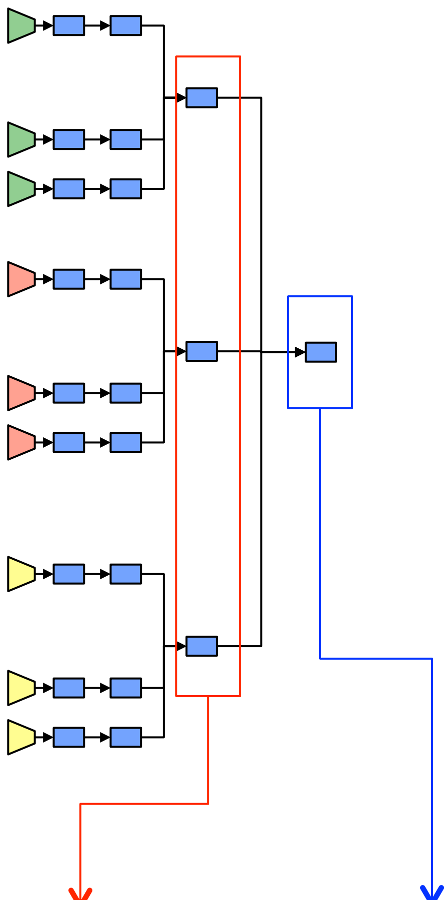
Lean but not mean enough.

Power Sum



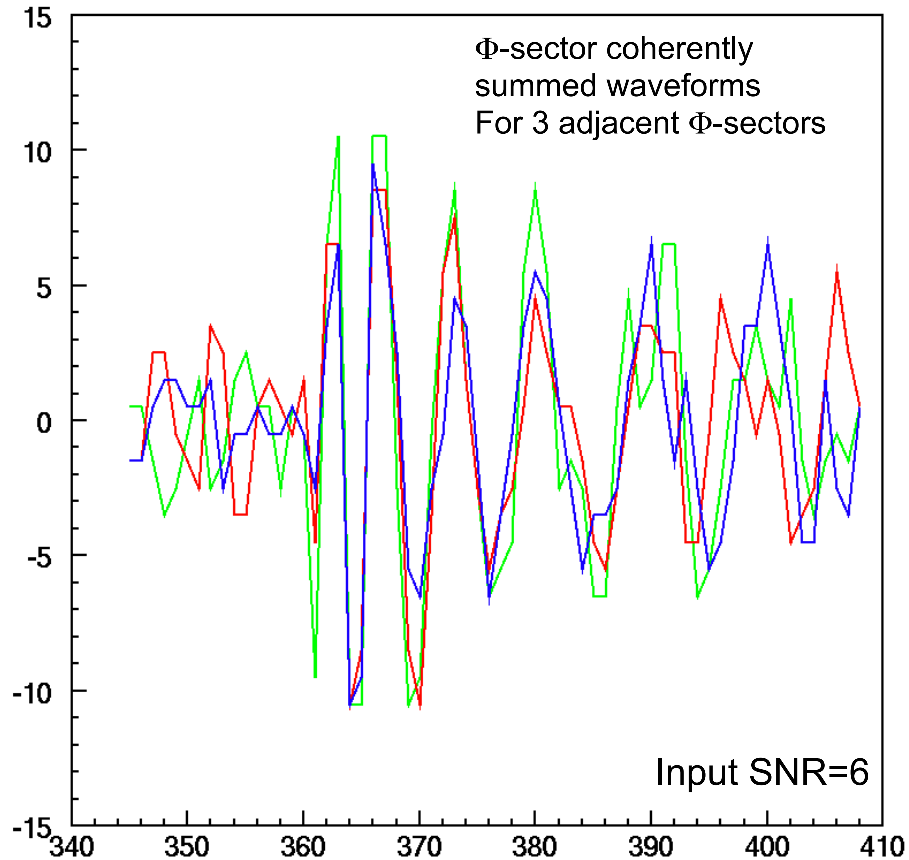
- 50% efficiency at SNR of 2.3σ

Sum of Sums Trigger



Combine amplitudes for 3 antennas in each ϕ-sector

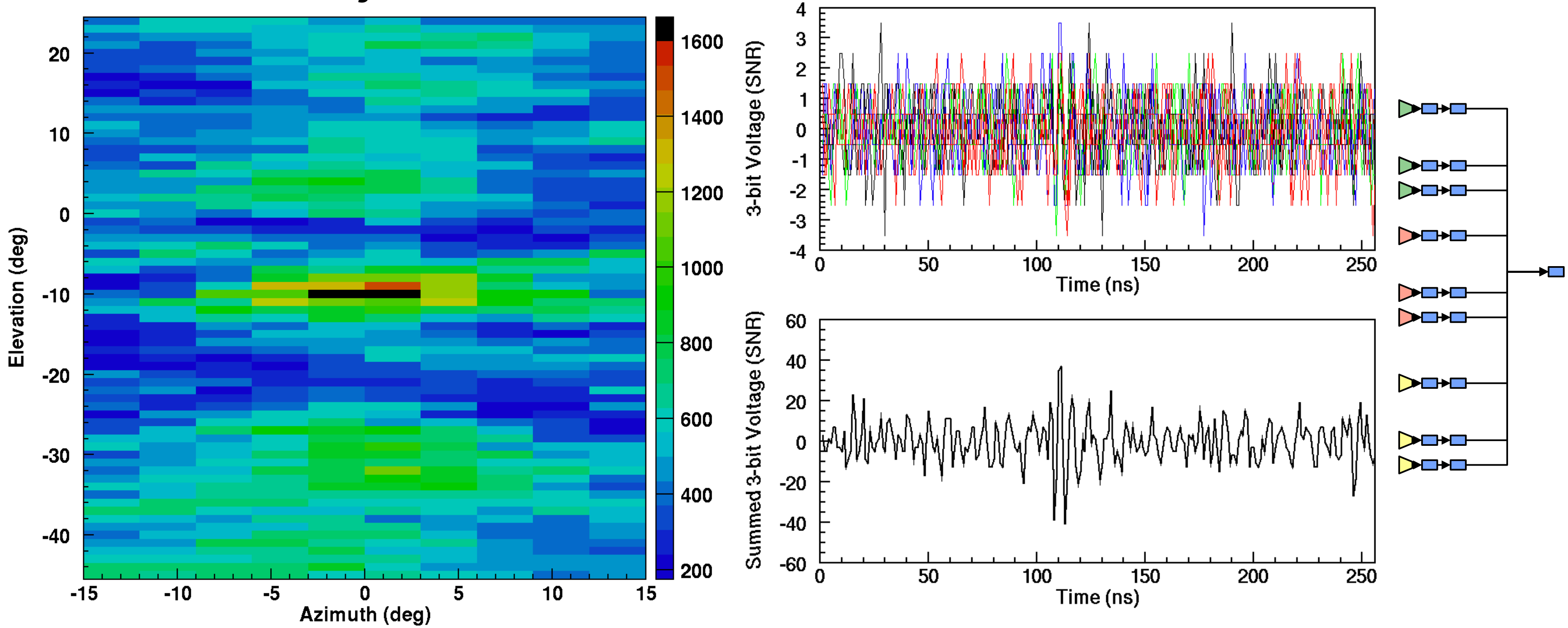
Combine amplitudes for each ϕ-sector



- 50% efficiency at SNR of 2.3σ
- Same as power sum performance, but with significantly higher operation counts.

Full Coherent Sum

SNR=2.0σ injected waveform



Δθ=1 deg x Δϕ=3 deg power map

- 50% efficiency at SNR of 2.0σ
- Too many operations and expected power consumption for a first try at this trigger.
- Perhaps a viable upgrade after success if proven with the ANITA-3 trigger.

Summary of Results

Trigger Type	50% Eff. SNR at an Accidentals rate of 100 Hz
Tunnel Diode	2.9
Single Phi-Sector Trigger	2.5
Power Sum	2.3
Full coherent sum (3 Φ-sector)	2.0

- Full coherent sum gives best results at the cost of added complexity.
- Due to development schedule constraints the power sum option was selected.

Power Sums vs. Cross-Correlations

- Coherent waveform sum vs. cross-correlation.

50% Eff. SNR at 100 Hz Accidentals	
Power Sum	2.32
Xcorr Sum	2.40

- Robustness against CW.
- Effects of uneven gains and variations.

Power Sum vs. Xcorr Efficiencies in the Presence of CW

CW source is from the same phi-sector as the pulse but random elevation and azimuth.

CW Amplitude (σ)	50% Eff. SNR at 100 Hz Accidentals	
	Power Sum	Xcorr Sum
0.0	2.32	2.40
0.1	2.32	2.40
0.5	2.33	2.49
1.0	2.41	2.50
2.0	2.65	2.92

Power Sum vs. Xcorr Efficiencies for Channels with Uneven Gains

Noise remains unchanged.

Overall amplitude gain factor of the pulse is varied.

Channel to Channel SNR Variations (%)	50% Eff. SNR at 100 Hz Accidentals	
	Power Sum	Xcorr Sum
0	2.36	2.44
10	2.36	2.45
20	2.36	2.48
30	2.30	2.35
50	2.25	2.37

At 20% the results of each run varies by 0.05
At 30% the results of each run varies by 0.1
At 50% the results of each run varies by 0.2

3-bit Digitizer Development

RITC
Realtime Independent Three-bit Converter

Second version has been fabricated.
Tested at the University of Hawaii.
~52 mW power consumption.
~ 2 Watts for all ANITA channels.

<u>Some other digitizers</u>

- Analog devices ADC083000:
  - 8 bit, single channel, 3 GSa/s
  - 1.9 W
- ALMA digitizer (0.25 μm BiCMOS)
  - 3 bit, single channel, 4 Gsa/s
  - 1.4 W [ALMA Memo No. 532]

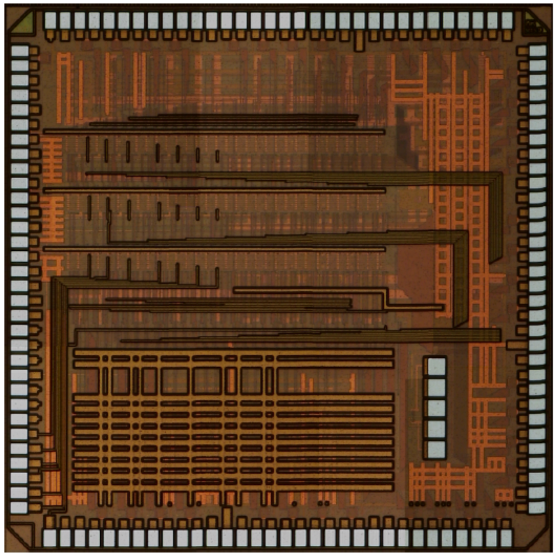


Fig. 4. Die photograph of RITC, as fabricated. The die size is 3.13×3.13 mm^2.

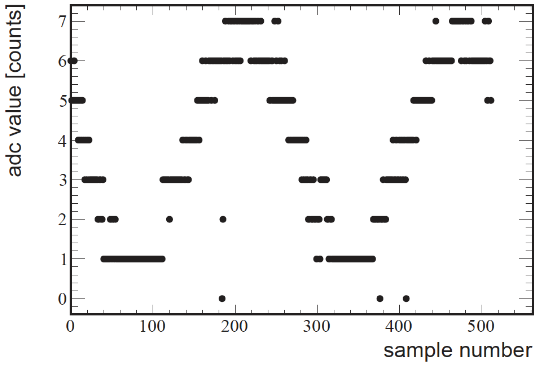


Fig. 13. A 2 MHz sine wave, as digitized into 3-bits by RITC at a sampling rate of approximately 510 MSa/s. Comparator threshold levels are chosen to be roughly uniformly spaced near the region of minimum comparator nonlinearity.

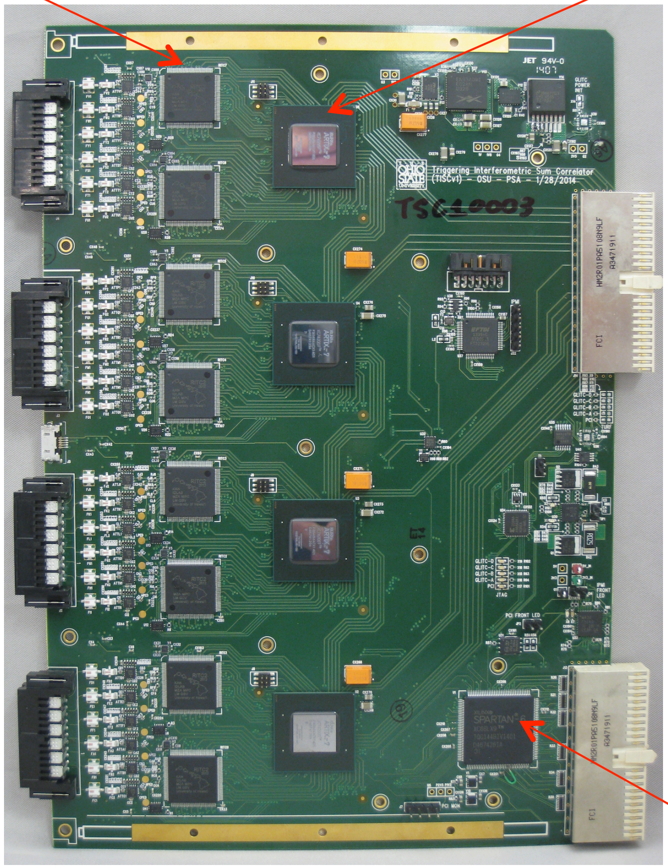
Nishimura et al., arXiv: 1203.4178

Trigger Interferometric Sum Correlator Board

RITC 3-bit digitizer, 3 channels per chip.

ARTIX-7 FPGA for with real-time digital beam-forming

Signals from antennas



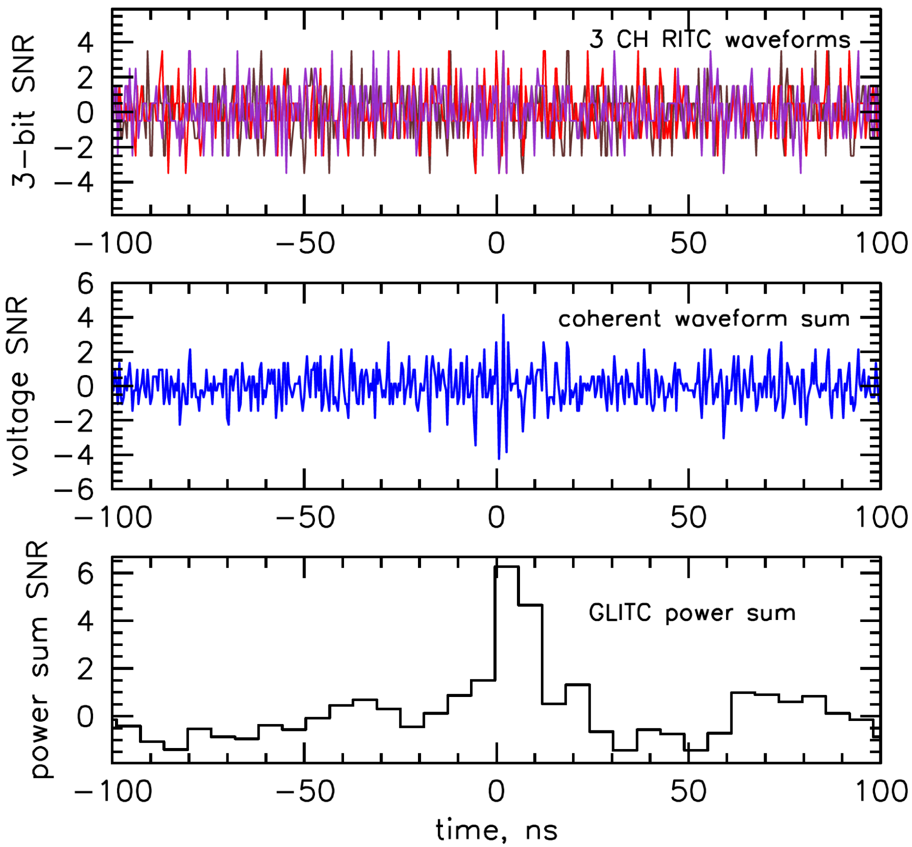
Power sums to global trigger decisions

to cPCI

FPGA for cPCI comms.

Hardware Test Results

SNR 2.0 injected signals



Conclusions

Pulse-phase interferometry offers highly sensitive techniques for analysis of ultra-high energy particle impulsive transients.

Implementation of this technique into a real-time digitization and triggering scheme can yield improvements in detection sensitivity.

Research described herein done under contract with NASA.
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Government sponsorship acknowledged.

Backup Slides

Uneven Timing Effects

- Procedure

  -Create Gaussian distributed timing offsets.

  -Create evenly sampled noise + signal waveform.

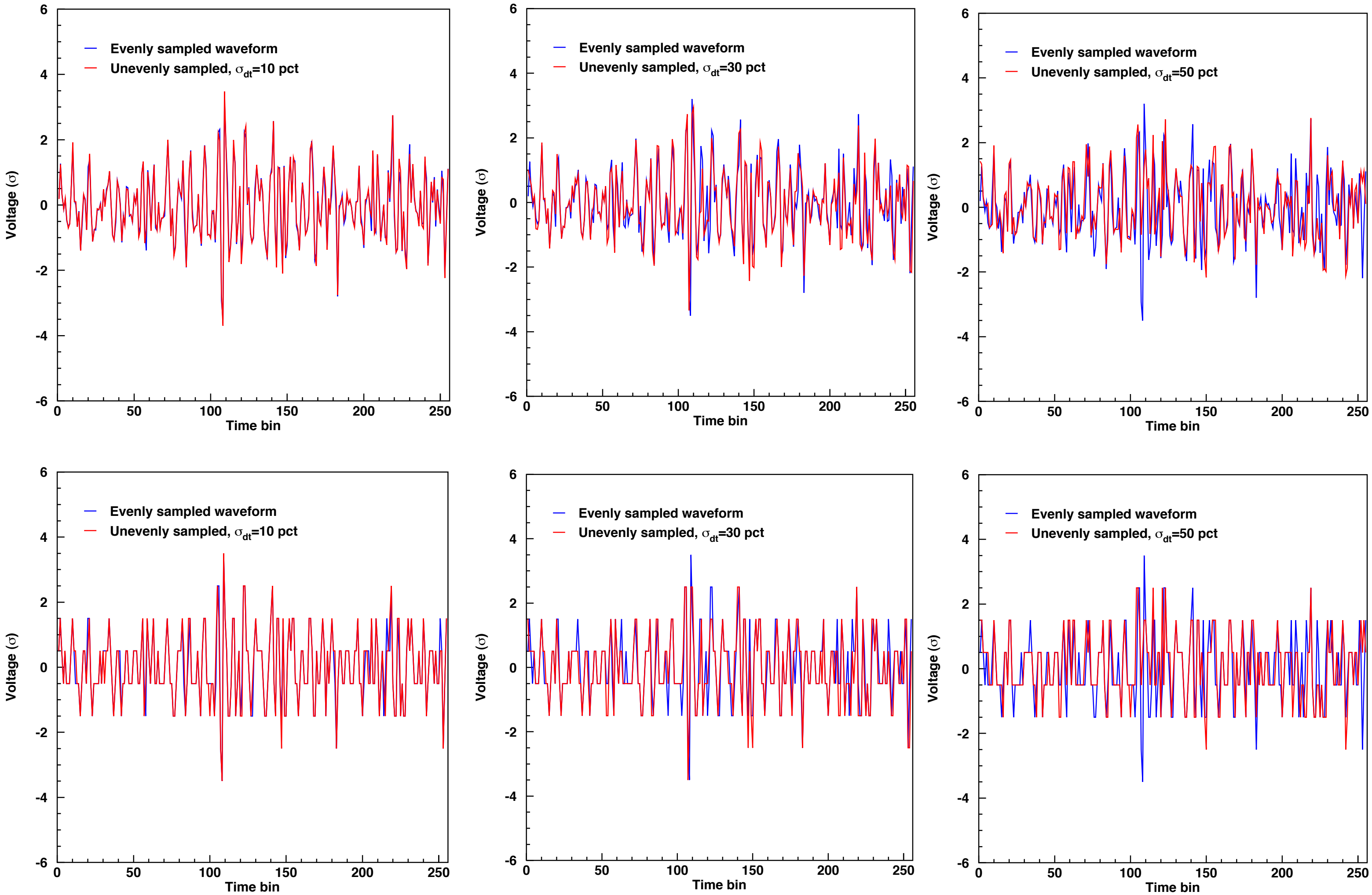
  -Use Fourier interpolation to reassign the voltage of each bin according to its timing offset. (Slow, there is no benefit from using an FFT for this procedure).

Unevenly sampled waveform examples.

Time sample variance = 10% | Time sample variance = 30% | Time sample variance = 50%

Waveforms

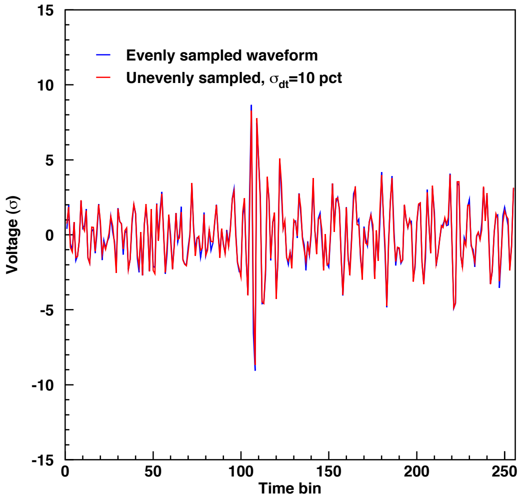
3-bit digitized waveforms

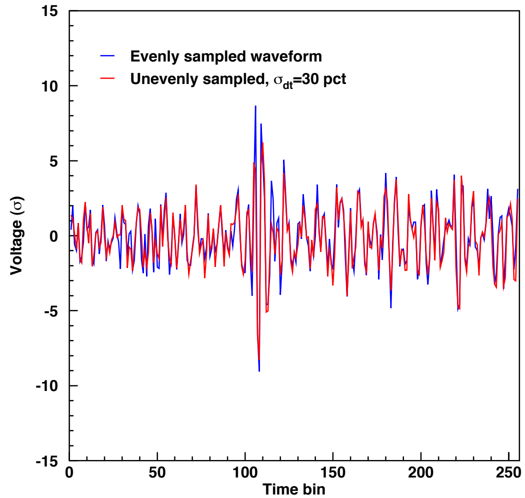


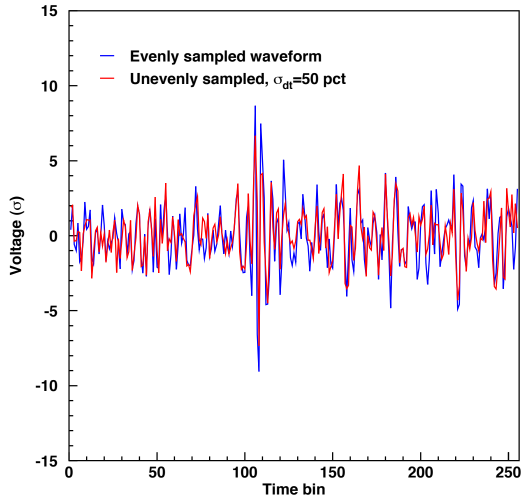
Unevenly sampled summed waveform examples.

Time sample variance = 10% | Time sample variance = 30% | Time sample variance = 50%

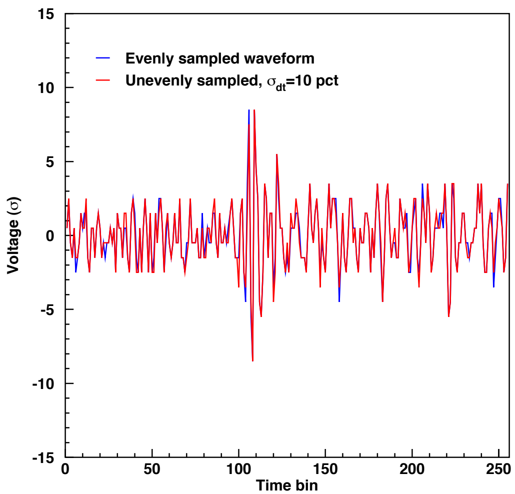
Coherently Summed waveforms

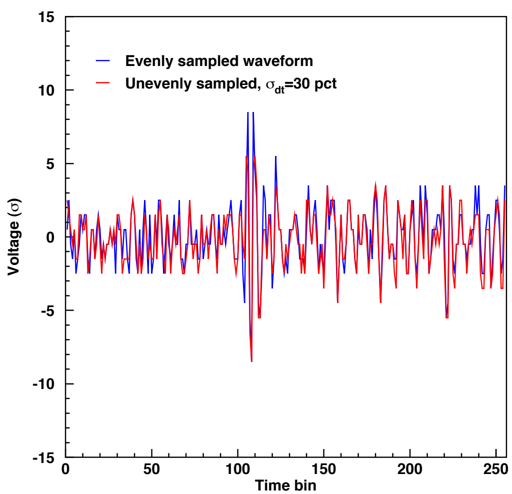


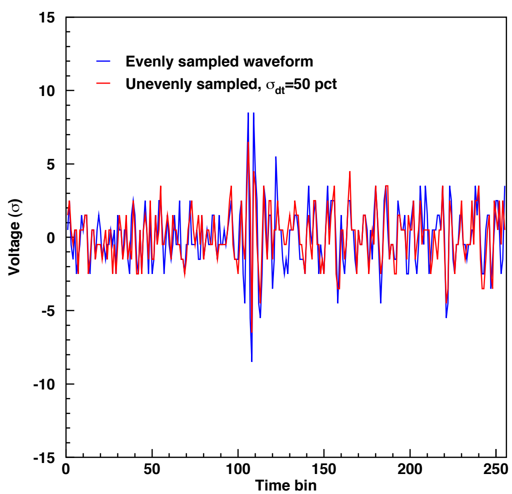




Coherently summed 3-bit digitized waveforms

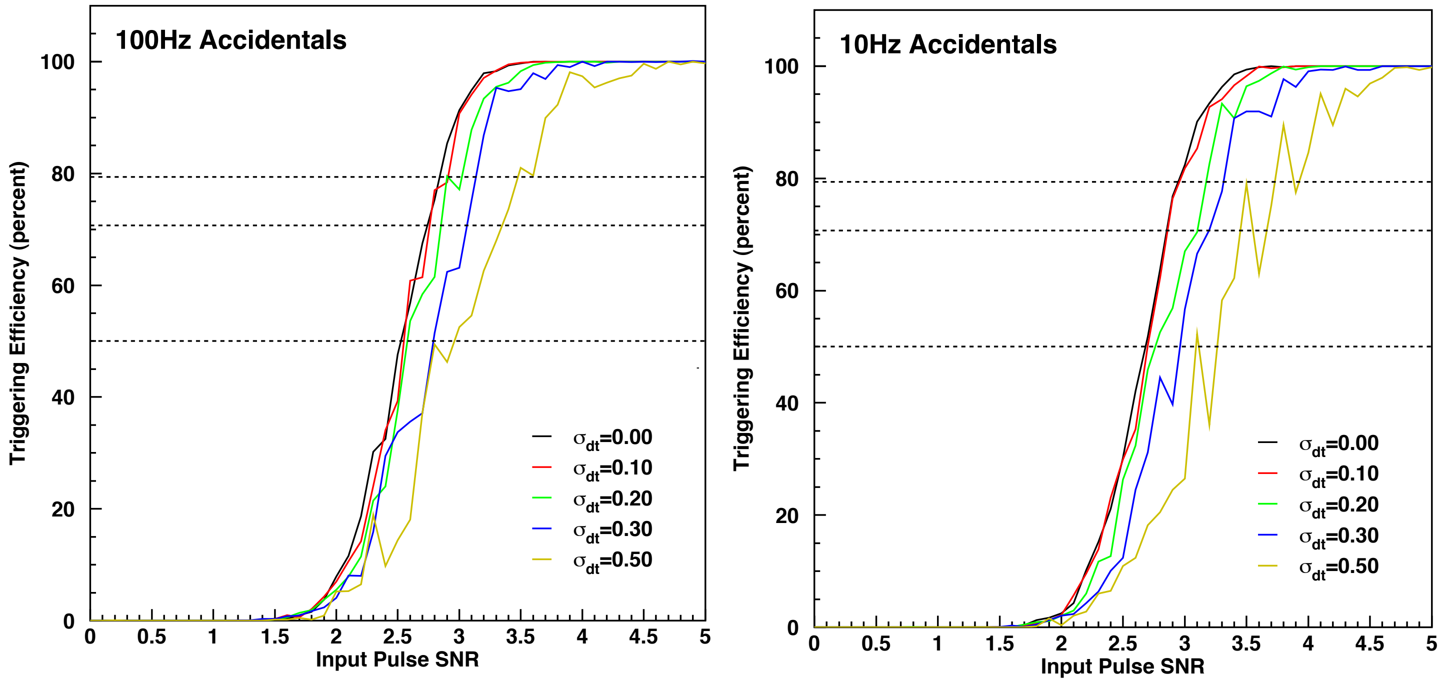






Uneven Timing Effect on Trigger Efficiency

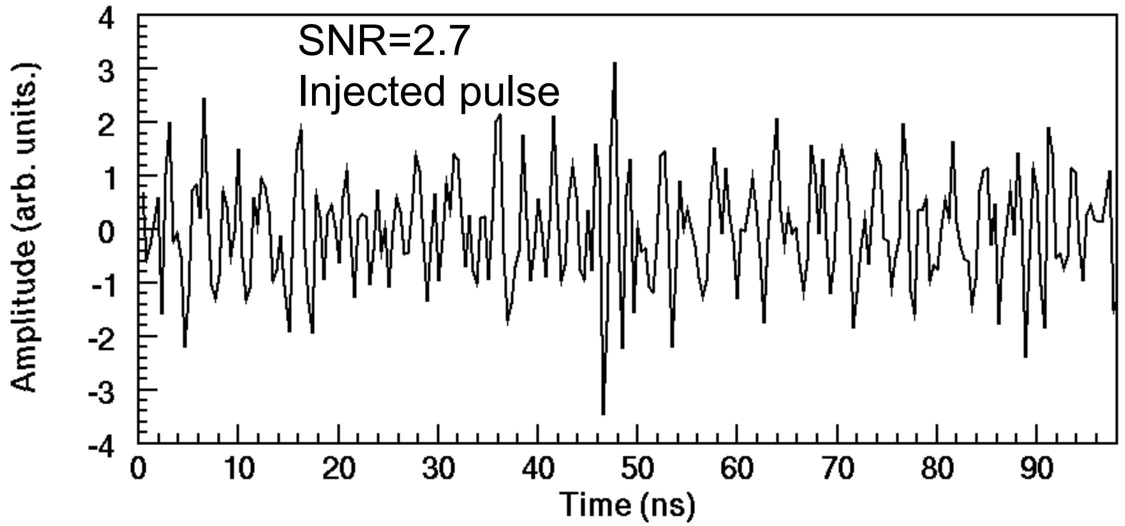
For various single ϕ-sector accidentals rates

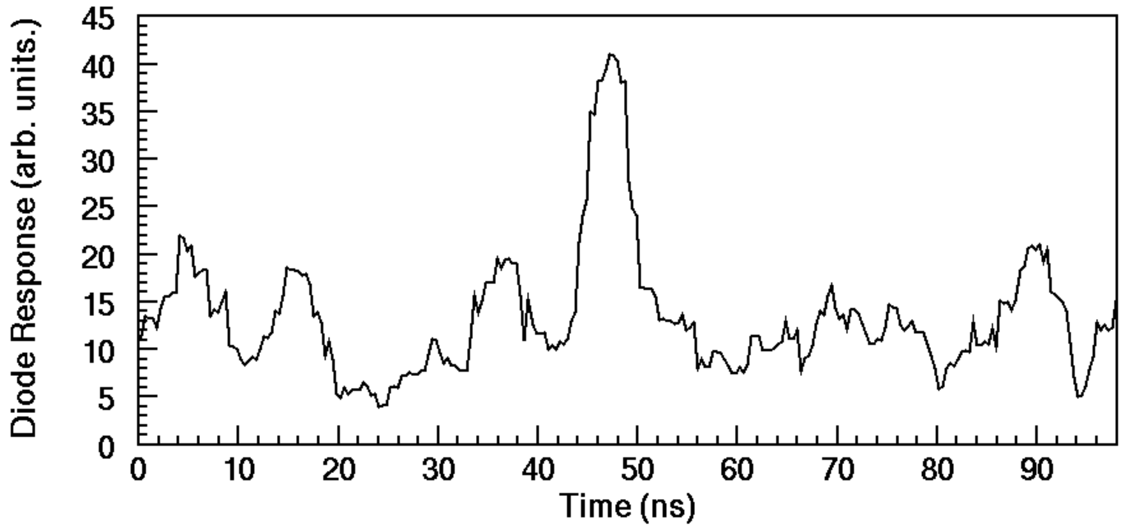


ANITA data recording digitizers, built with the same process, have ≤ 15% sample timing variance.

Tunnel Diode Simulations (1): Trigger Setup

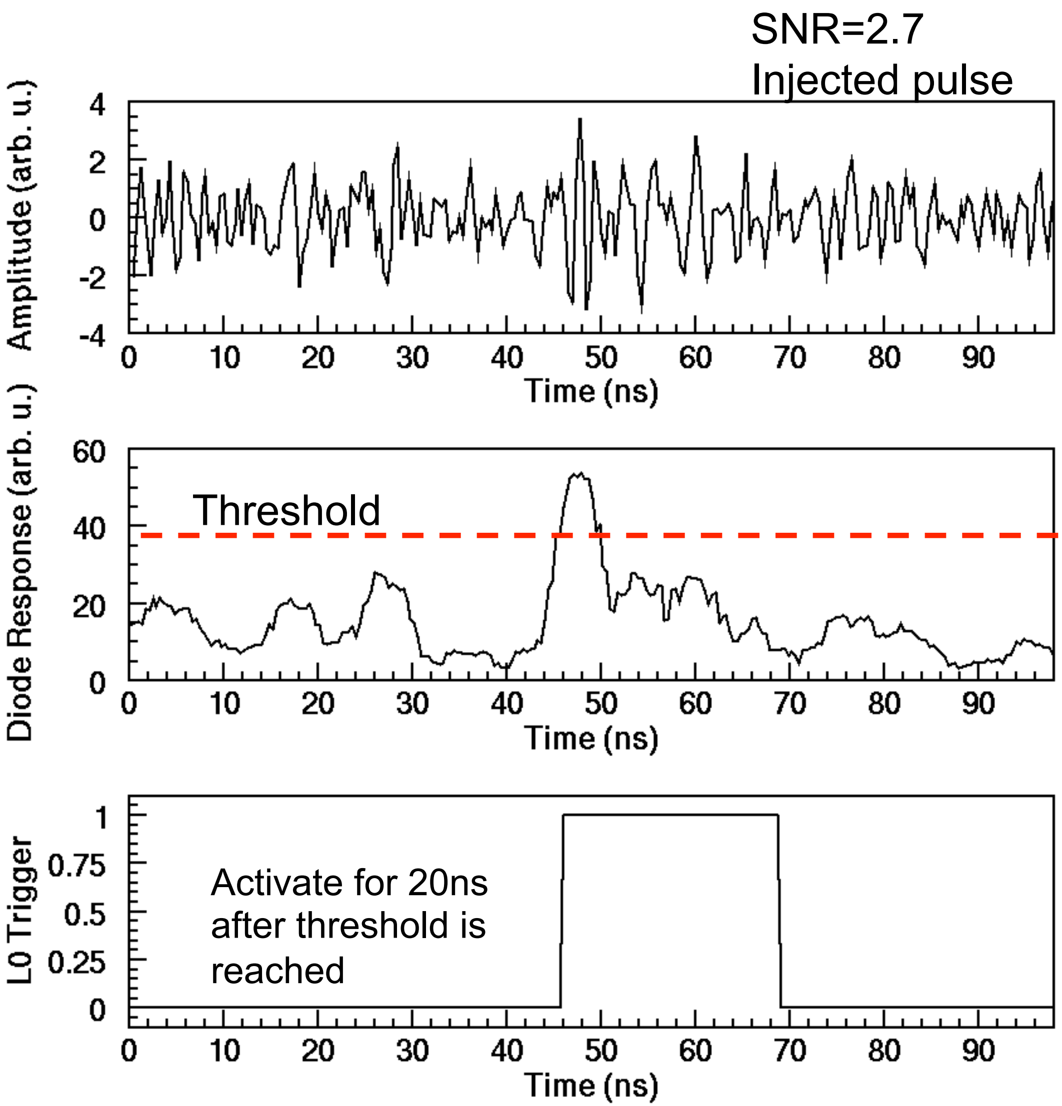
Tunnel diode response: integrate the square of the voltage over 5ns period.



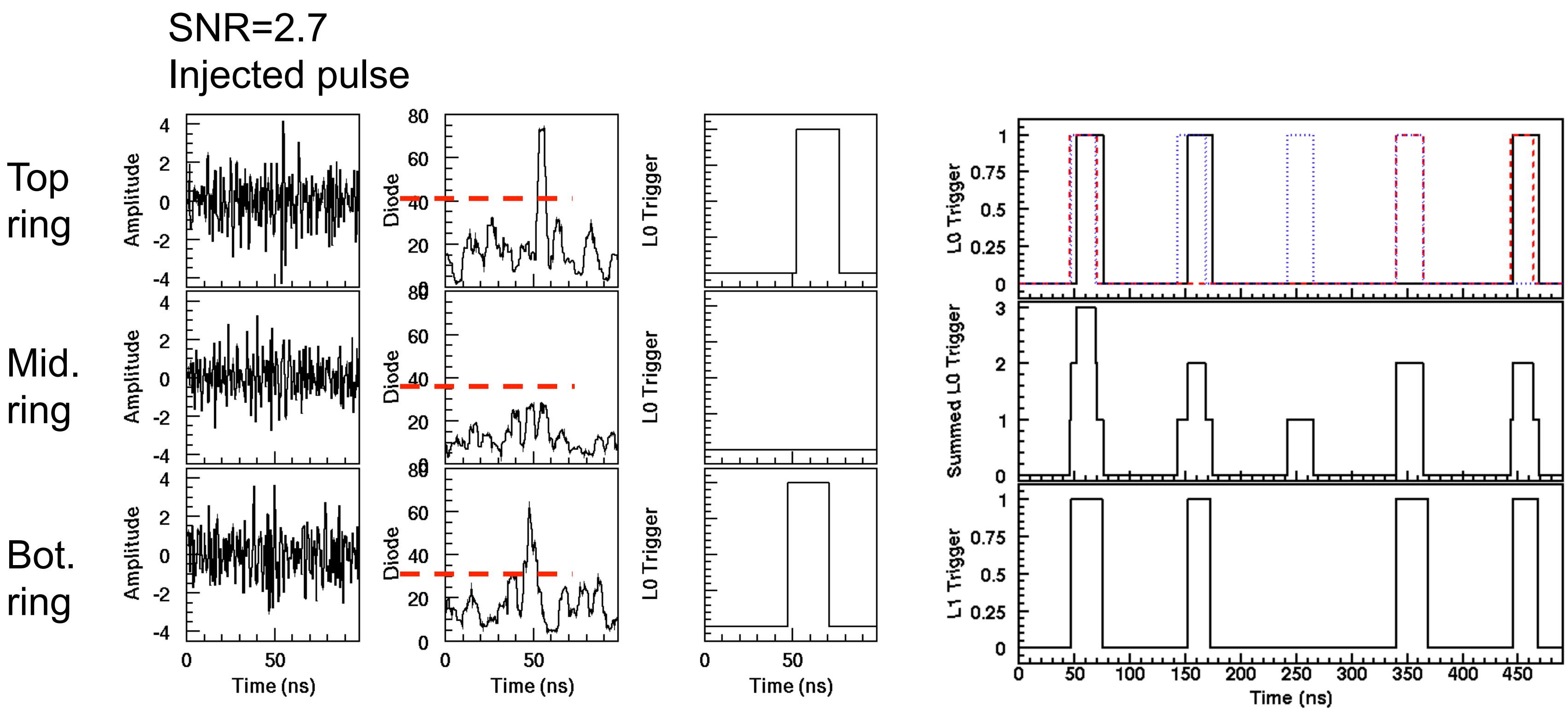


Tunnel Diode Simulations (2): L0 Trigger

L0 Trigger: If the diode trigger exceeds a defined threshold, the L0 trigger is activated for 20ns. This time window is defined by the maximum possible delay between the top antenna and the bottom antenna in a phi-sector.



Tunnel Diode Simulations (3): L1 Trigger

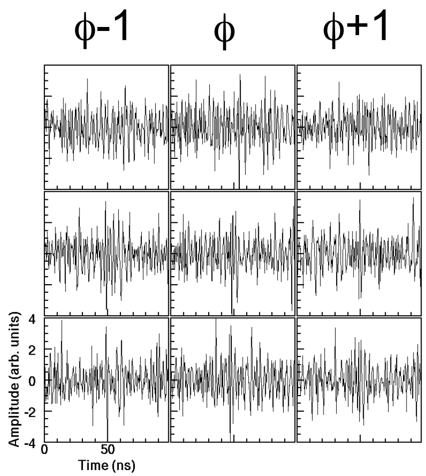


L1 Trigger: Check for L0 trigger coincidence between three antennas in a a given phi sector. If coincidence is met, the L1 trigger window is activated by 5 ns. This time window is defined by the

60

Tunnel Diode Simulations (3): L2 Trigger

L2 Trigger: Require an L1 coincidence between two neighboring phi-sectors. In my sim, trigger deactivates for 50ns (20MHz max rate.)



Example of SNR=3.2 waveforms incident on boresight.