A Real-time Digital Beam Forming Trigger for Radio Detection of Ultrahigh Energy Particles

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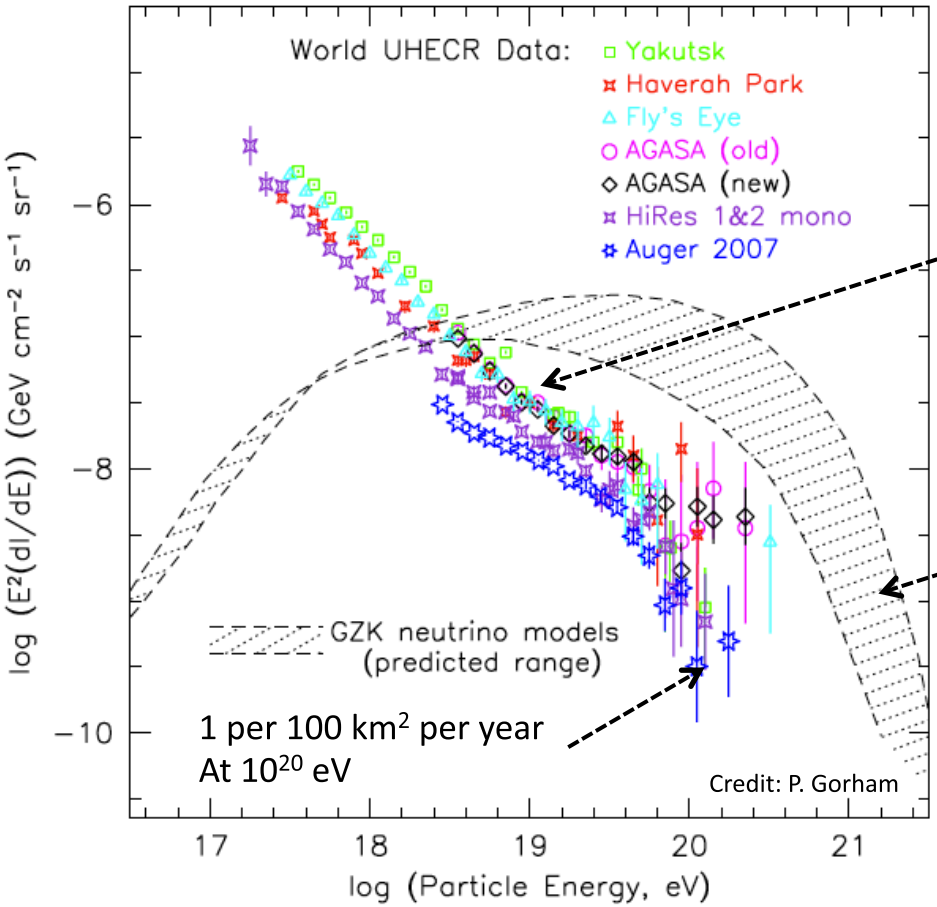
Outline

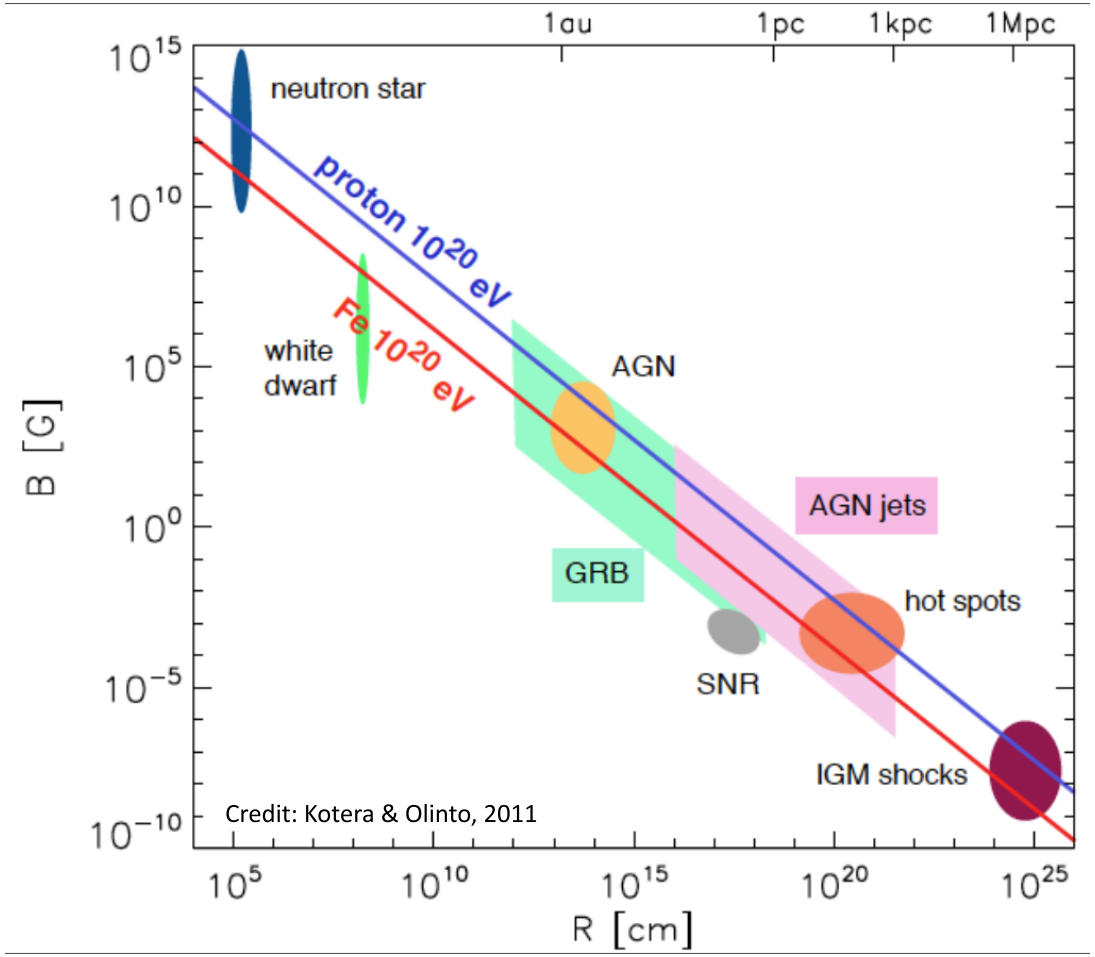
- What are ultrahigh energy particles and why do we care about them?
- Radio Detection.
- The ANITA Experiment
- Triggering
- Future prospects

Ultrahigh Energy Particles



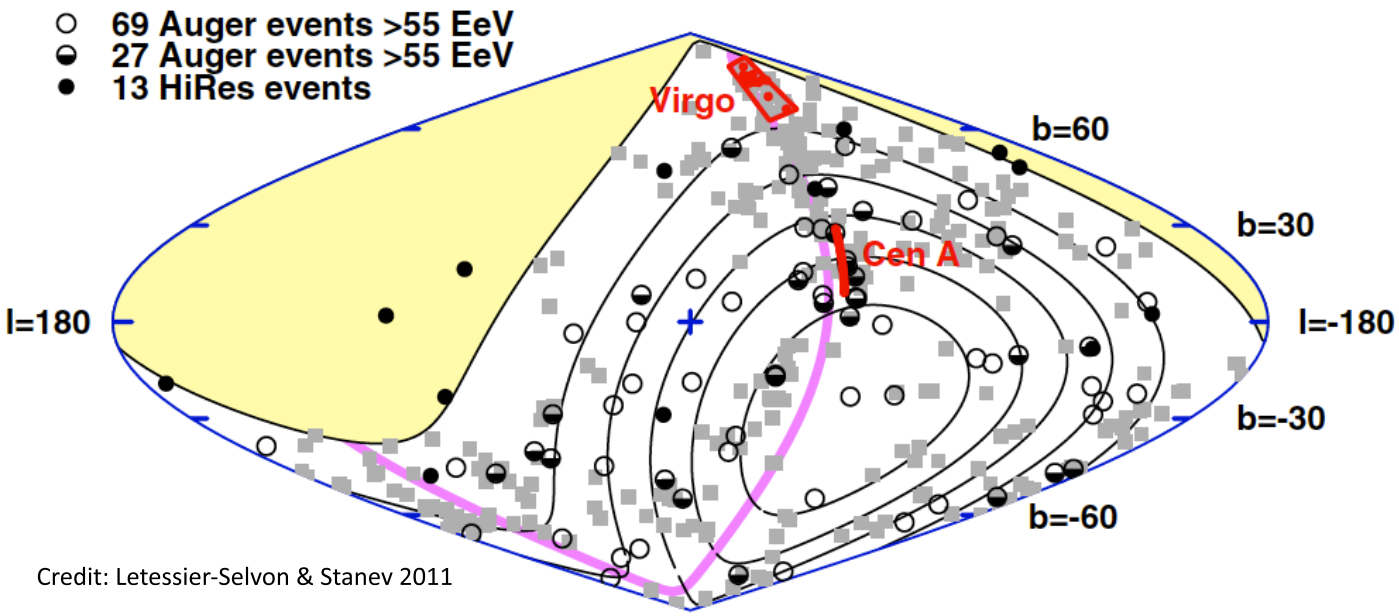
- Energies >10^{19} eV
- Cosmic rays (protons or heavier nuclei) have been measured by many ground array experiments.
- Neutrinos, none measured at these energies but many models predict fluxes comparable to cosmic rays.

Cosmic Ray Candidate Sources



- Acceleration potential of a source is proportional to magnetic field strength × size
- Acceleration sites and mechanisms still remain a mystery largely due to intergalactic magnetic field scattering.

Cosmic Ray Astronomy



Credit: Letessier-Selvon & Stanev 2011

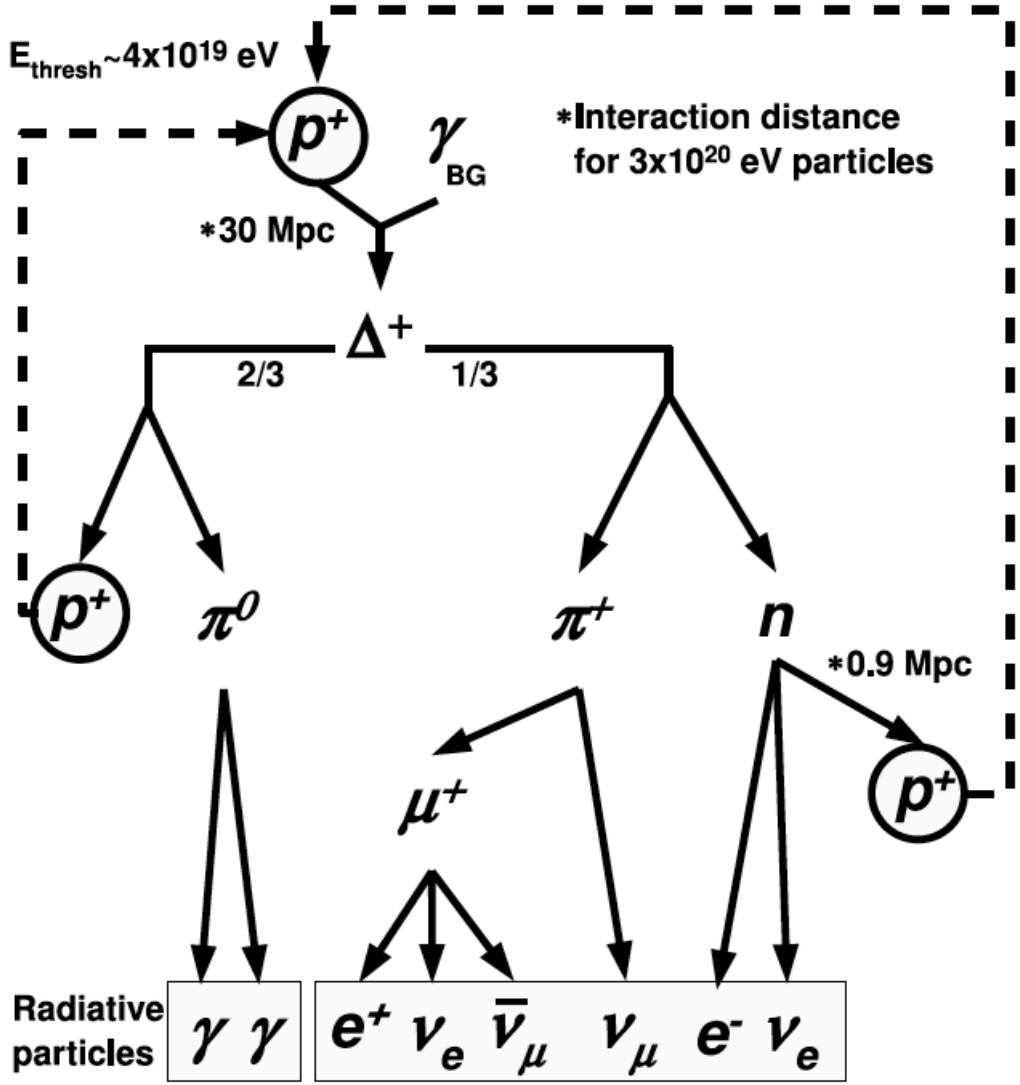
- Evidence of source correlation to Veron-Cetty & Veron AGN catalog with redshifts z < 0.018 (distances < 75 Mpc) and within 3.1° separation angles. (Abraham et al. 2007, 2008).
- Currently correlation has a 3σ level significance (Abreu, 2010)
- HiRes claims no statistically significant correlation on 13 events with energy > 5.5×10^{19} eV.
- Extragalactic magnetic field scattering uncertainties can be >15° according to some models (Armengaud, Sigl, Miniati 2004) , (Ryu, Das, and Kang 2010)
- Need more events and higher energies to do this.

UHECR Propagation

- Cosmic photon backgrounds attenuate UHECR energy
- Interaction threshold at $4x10^{19}$ eV
- UHECRs observed with $E>4x10^{19}$ eV must be within 100 MPc

<u>Cosmic Distance Scales</u>
Milkyway: 30 kpc
Andromeda: 800 kpc away.
Cen A: 4Mpc
Virgo Cluster: 17 Mpc
Coma Cluster: 90 Mpc

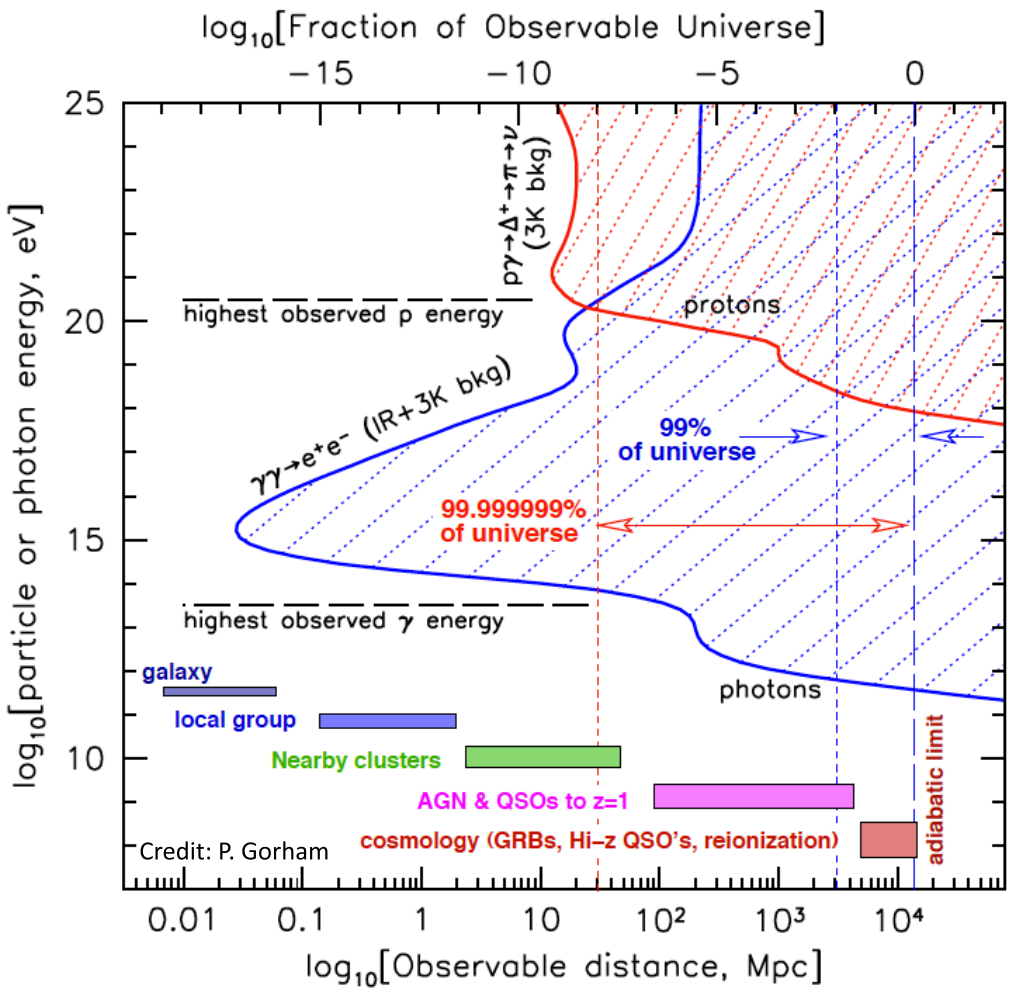
Schematic of the GZK Process and BZ Neutrino Production



Credit: A. Romero-Wolf, PhD thesis.

Neutrino Astronomy

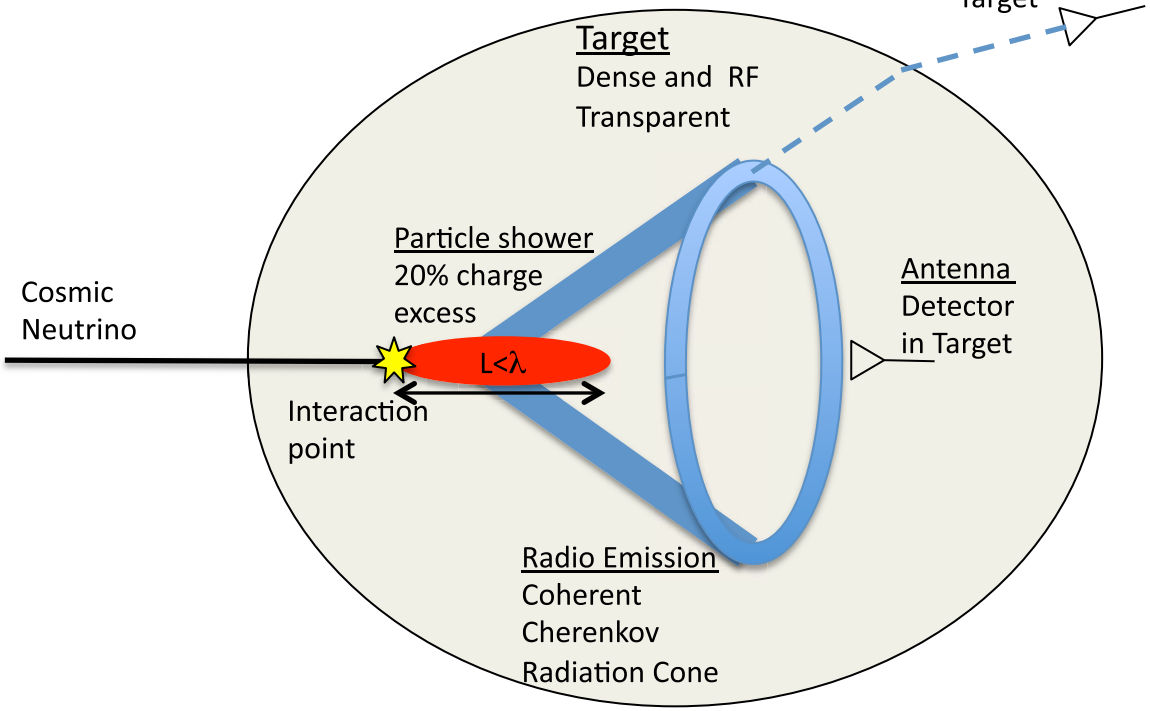
- Neutrinos are unimpeded by cosmic photon backgrounds.
- Neutrinos are undeflected by magnetic fields revealing there sources all the way back to the beginning of time.
- Guaranteed background exists from UHECR propagation.
- Provide the best window to the high energy universe (if only we could detect them).

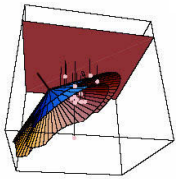


UHE Particle Detection

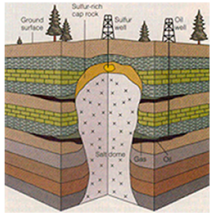
	Neutrinos	Cosmic-rays
Interaction	Very small cross-section, deeply penetrating. Low chance of interaction unless target is dense and large.	Cross-section large enough to interact in the atmosphere a few km above sea level.
Particle showers	Produce a particle shower. The shower is compact (meter scale) and buried in a few km water equivalent of a target.	Produce extended air shower. Secondary particles detected by ground arrays
Other emissions	Radio Cherenkov radiation.	UV fluorescence, Radio geo-synchrotron radiation.

Neutrino Radio Detection

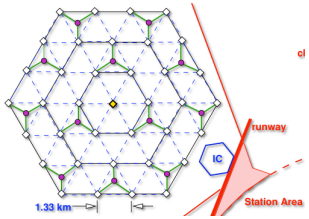




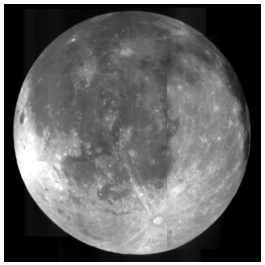
RICE
Dipole
antennas in
South Pole
ice.



SALSA
Antennas in
salt domes



ARA
Large
detector
antenna
network in
South Pole

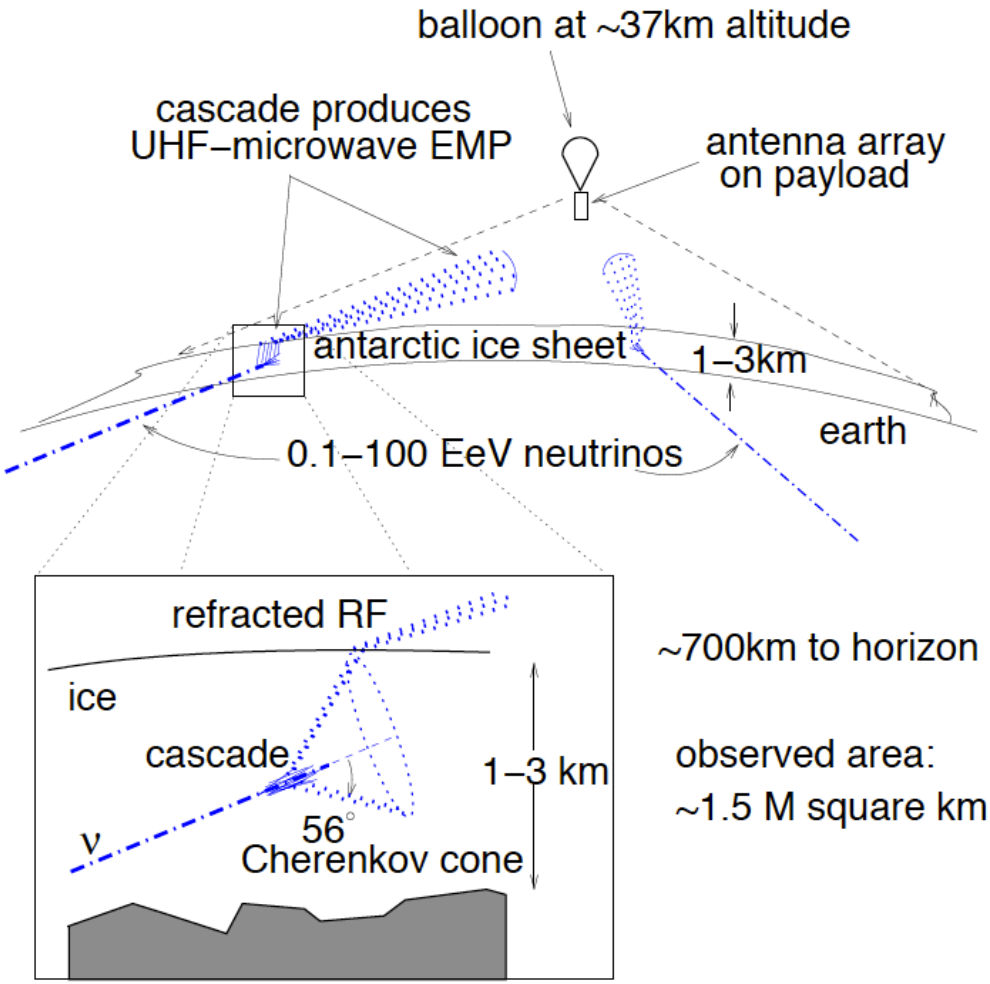


GLUE
Lunar
regolith
target with
DSN
antenna.

ANITA

Neutrinos

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



~700km to horizon

observed area:
~1.5 M square km

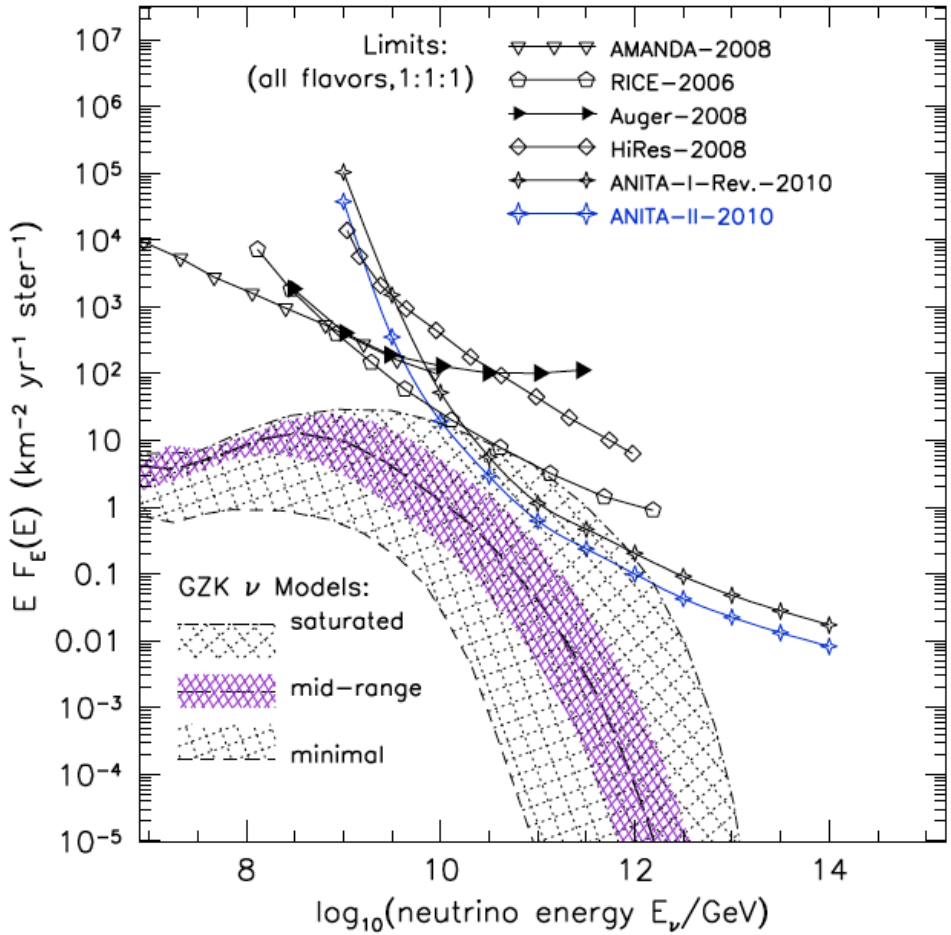
ANITA Results

Neutrinos

- Two flights
  - 2006-2007
  - 2008-2009
    Factor of two improvement in sensitivity.

Most sensitive ultra-high energy neutrino limits to date.

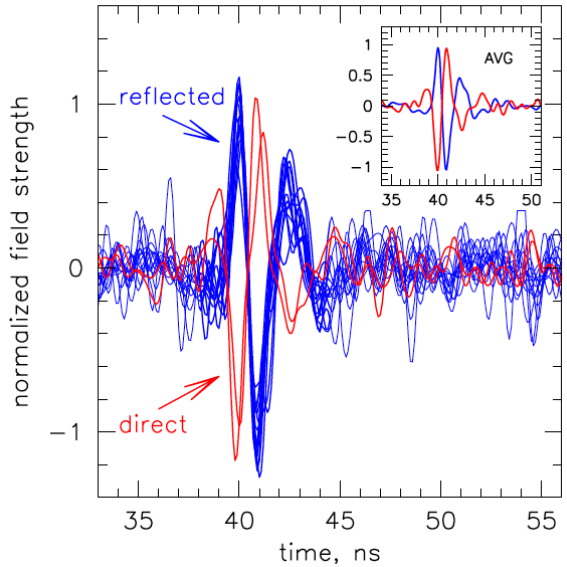
No neutrinos detected.

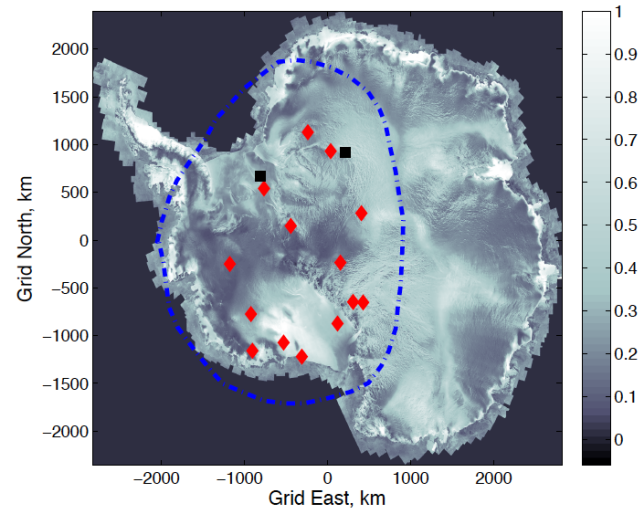


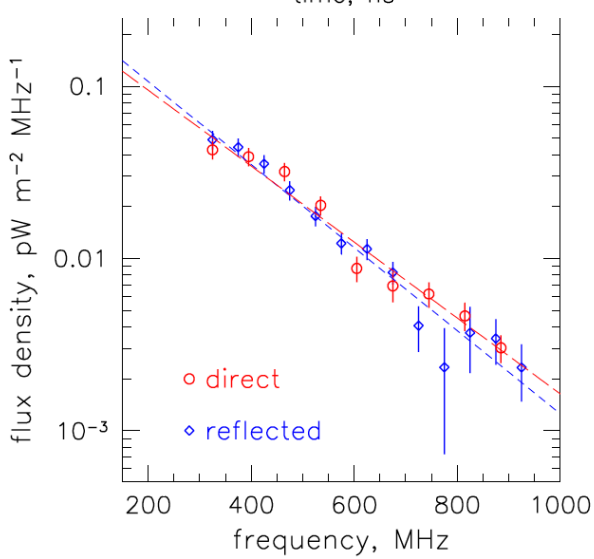
ANITA

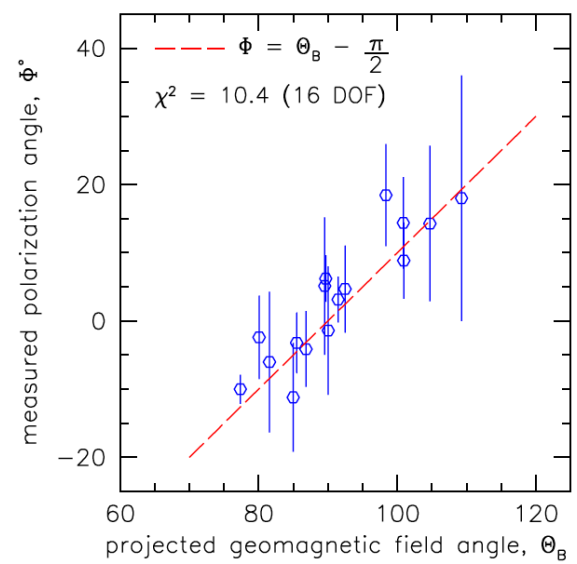
Cosmic Rays

- Unexpected observation of UHECRs
- 14 isolated events.
- Nearly identical pulse shape and spectra.
- Identified as UHECRs by the correlation of the polarization to the geomagnetic field angle. (Geo-synchrotron emission).









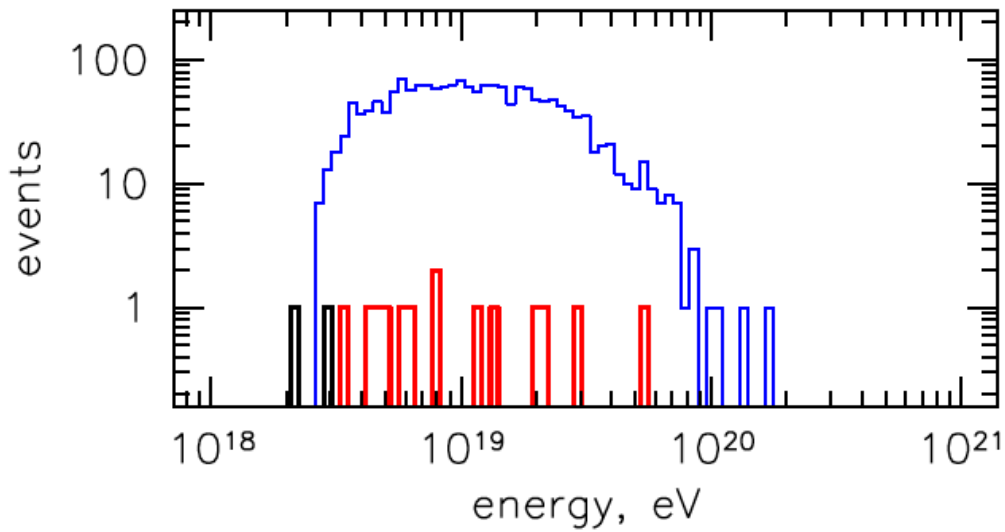
ANITA Results

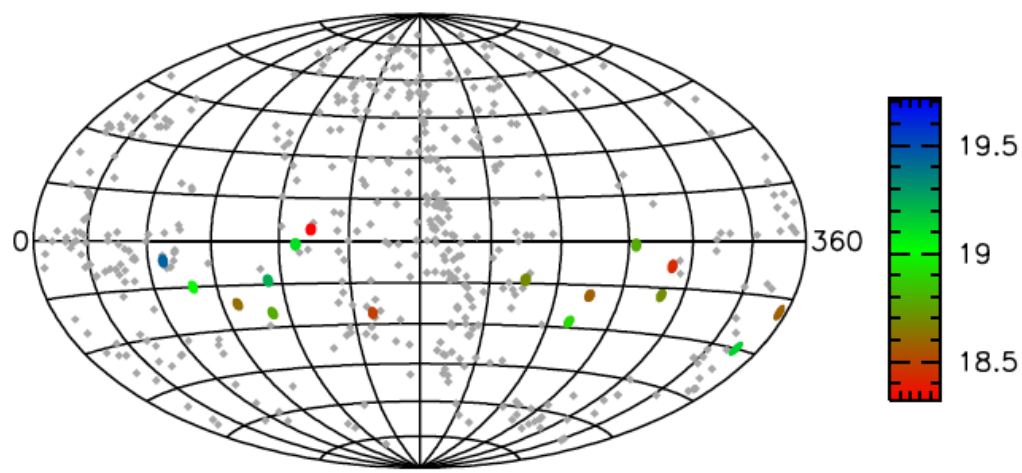
Cosmic Rays

Energy reconstruction sets the event energies at 10^{18}-5×10^{19} eV

ANITA-2 detected 3 UHECR events. (Optimized trigger for Vpol for neutrinos, UHECRs are Hpol).

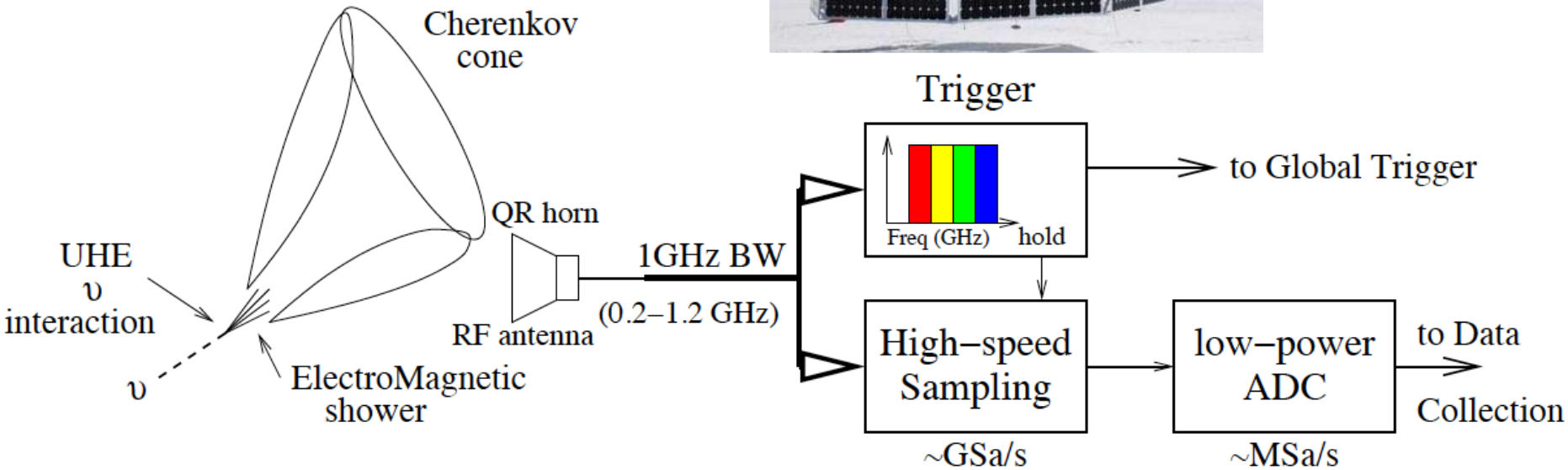
ANITA-3 scheduled for 2013-2014 will use an optimized trigger design and is expected to detect hundreds of UHECR events.





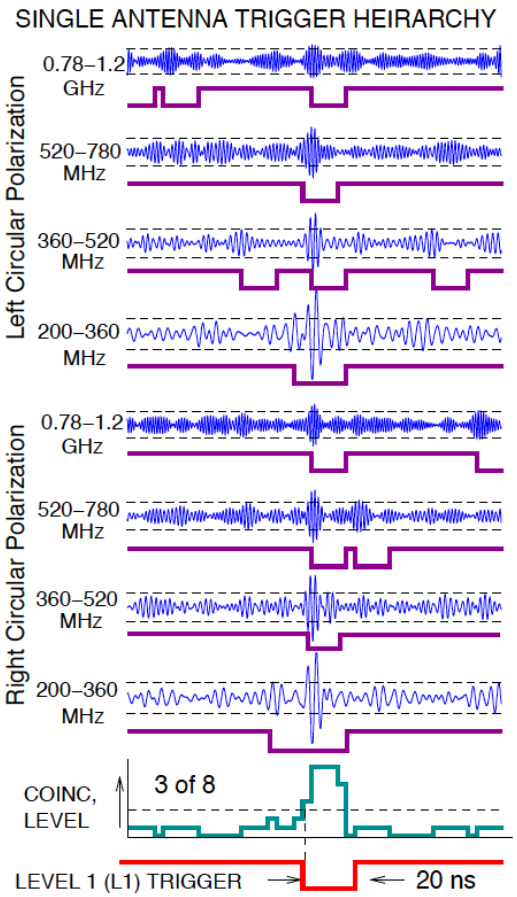
The ANITA-1 Trigger

- 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.



The ANITA-1 Trigger

Design Drivers	Implementation
Low power	Use tunnel diode detectors.
Protection against saturation	4 bands per polarization channel with roughly equal power and tunable threshold.
High sensitivity	2.3σ threshold on each frequency channel. Require coincidence in frequency bands and neighboring antennas.
Manageable data rate.	Servo thresholds for 5 Hz accidentals trigger rate.
Linearly polarized	Transform Hpol and Vpol signals to RCP and LCP via a hybrid. Then require roughly equal power levels.



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

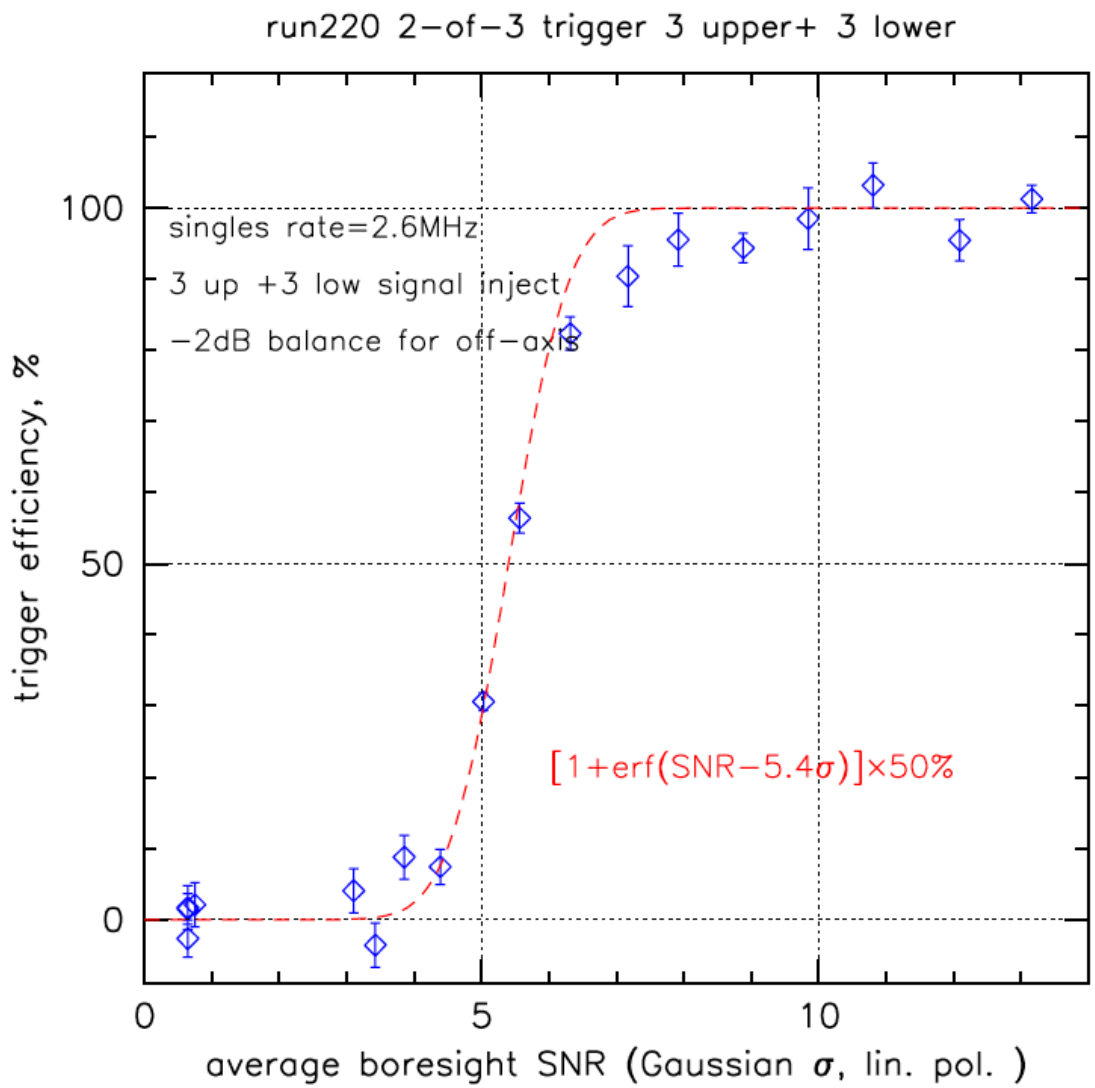
The ANITA-1 Trigger

Laboratory tests show a 50% efficiency at 5.4σ SNR.

SNR defines as peak amplitude of RMS noise (not power).

Performed well during flight.

18 days live time in 35 day flight.



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 Tentative ANITA-3 Trigger

Azimuthal masking: better solution against blasting anthropogenic backgrounds.

Forget sub-bands. We want to go for broke on this flight. We only really care about the sensitivity over deep quiet ice anyway.

Adding 8 more antennas. (Additional full bottom ring.)

Expect a 50% efficiency at 2.8σ SNR.

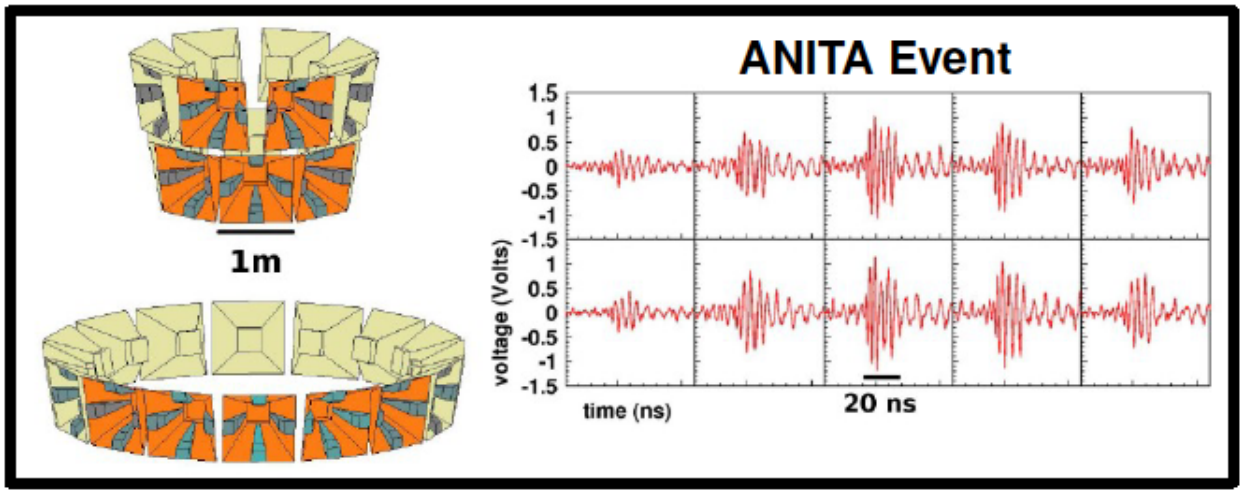
Design Drivers	**Implementation**
Low power	Use tunnel diode detectors.
Protection against saturation	Mask payload direction where excessive triggering occurs.
High sensitivity	Full band. Keep both Hpol and Vpol. (We want cosmic rays).
Manageable data rate.	Servo thresholds for 100 Hz accidentals trigger rate.
Linearly polarized	Run Hpol and Vpol independently. Two different physics channels, let them be.

ANITA Analysis

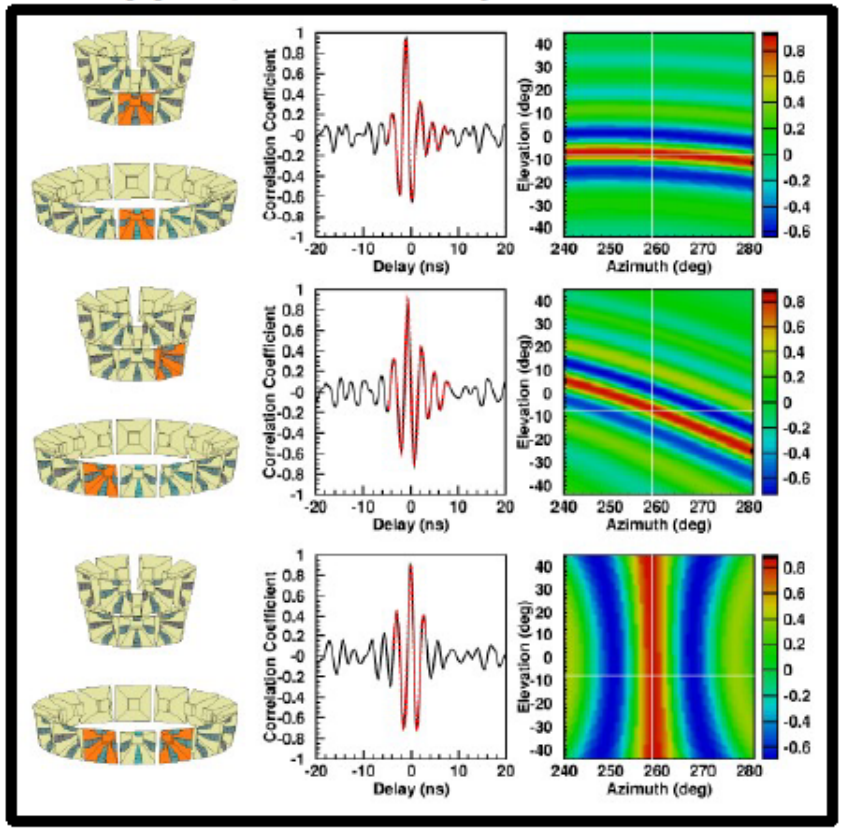
- ANITA-1 analysis was claiming a 50% efficiency at 2.0σ SNR while expecting a single thermal event for the live time of the experiment.

- The trigger was giving 50% efficiency at 5.4σ SNR with a 5 Hz accidentals rate.

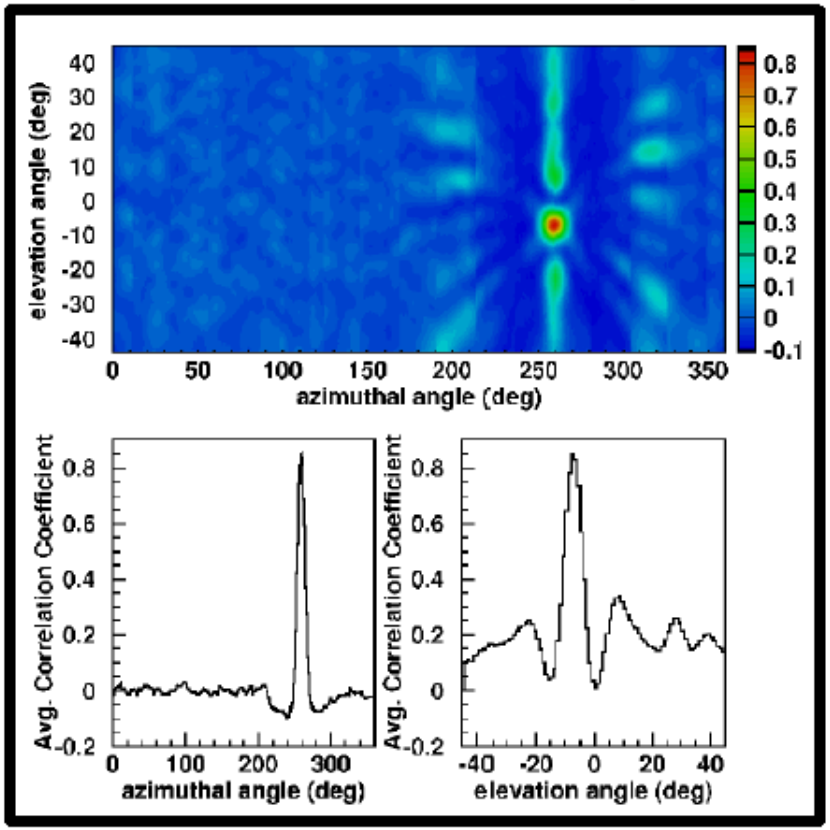
Mapping Waveforms to Interferometric Images



Mapping Time Delay Correlations



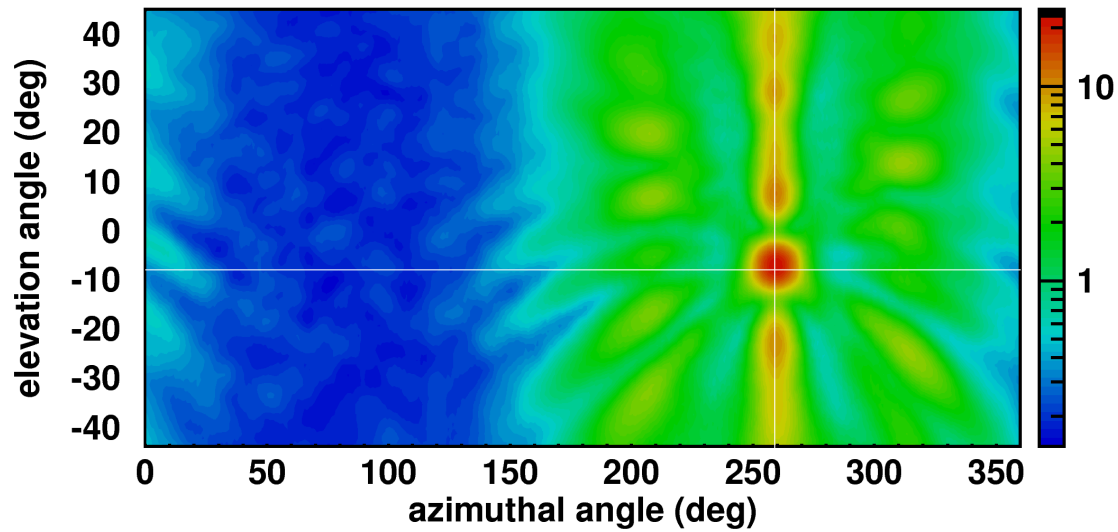
Interferometric Image

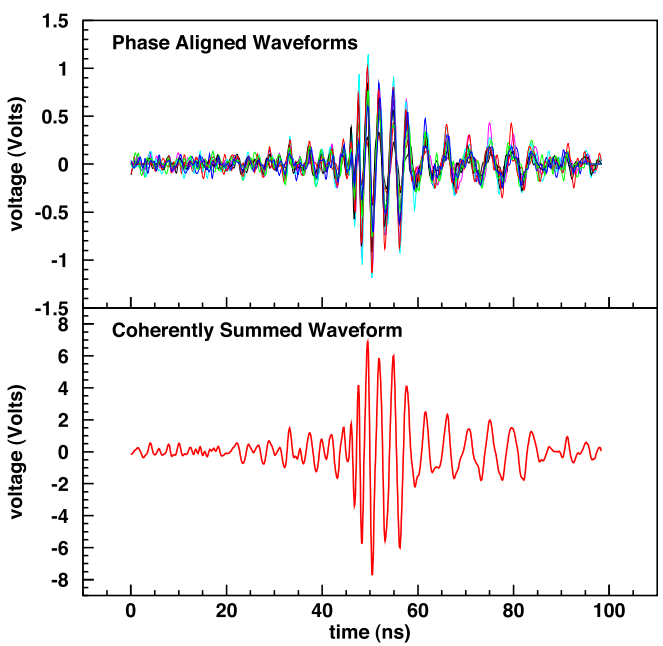


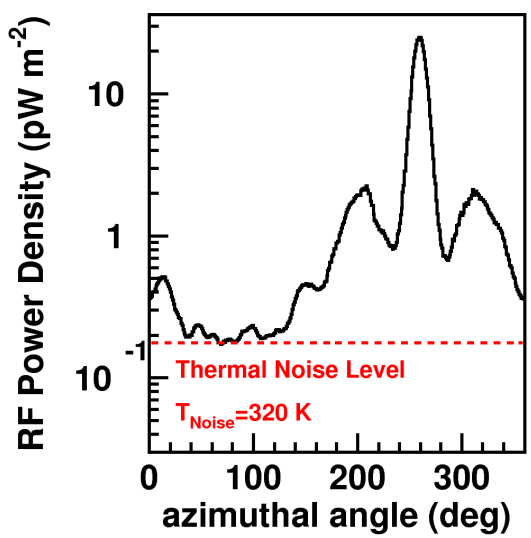
Phased Waveform Sum

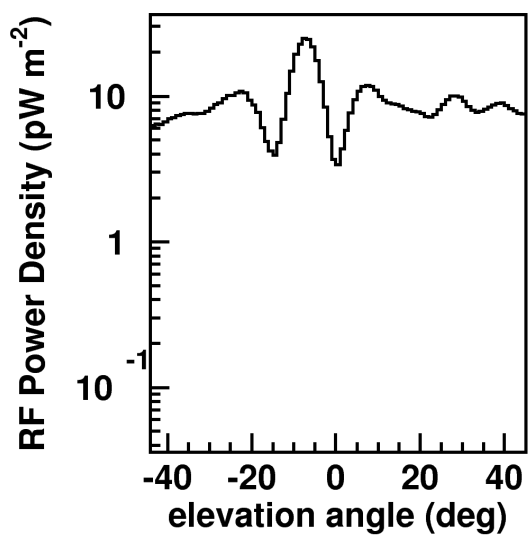
Impulse response for ANITA receivers are nearly identical.

Exploit this fact to add waveforms coherently and improve the signal to noise ratio.









How can we apply these principles to a real time trigger?

- Need a low power digitizer.
  - Use a low resolution (3 bits) at 2.6 Gsa/s.
  - Nothing of use to us out there so we need to fabricate an ASIC for it.

- Need a real-time way to combine signals.
  - FPGA, may be too much power.
  - ASIC is more power efficient.

Getting started

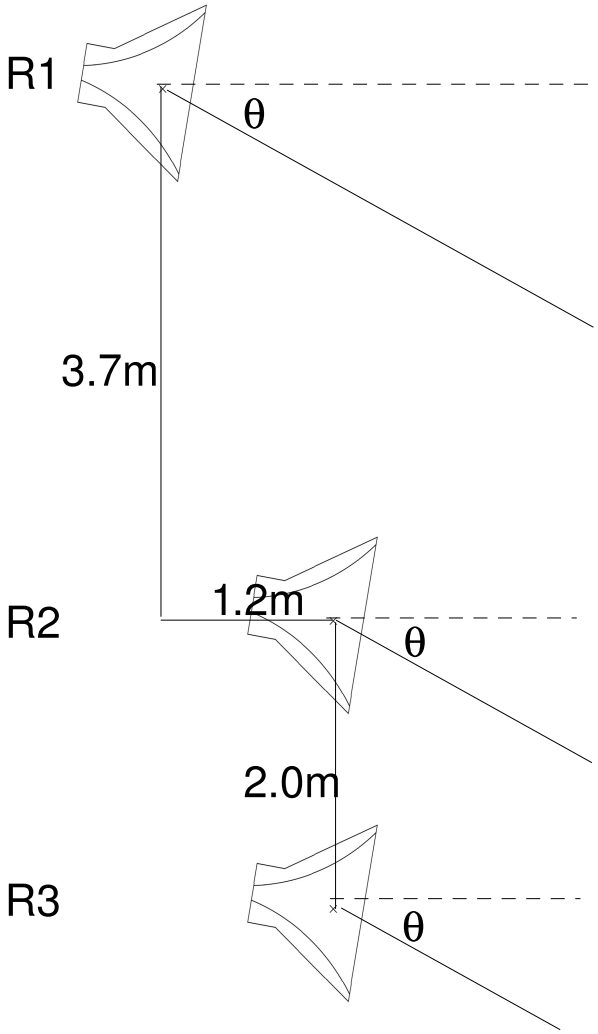
Approach

Start with a first cut at a signal combining trigger and vary parameters from there..

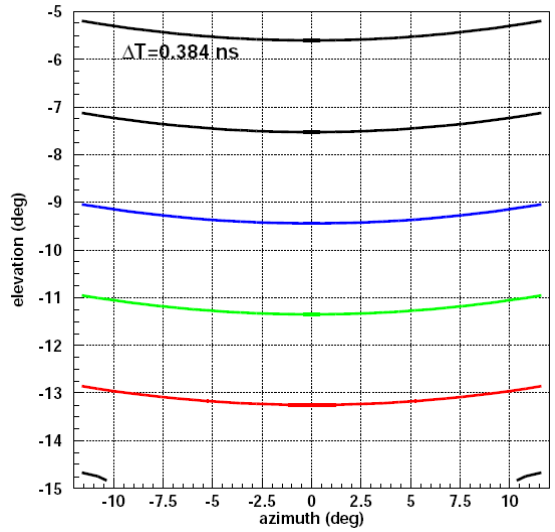
<u>Parameters</u>

- Number of directions to sample.
- Time window for pulse detection.
- Is 3-bits optimal? How should the levels be set?
- What kind of tolerances can we afford?

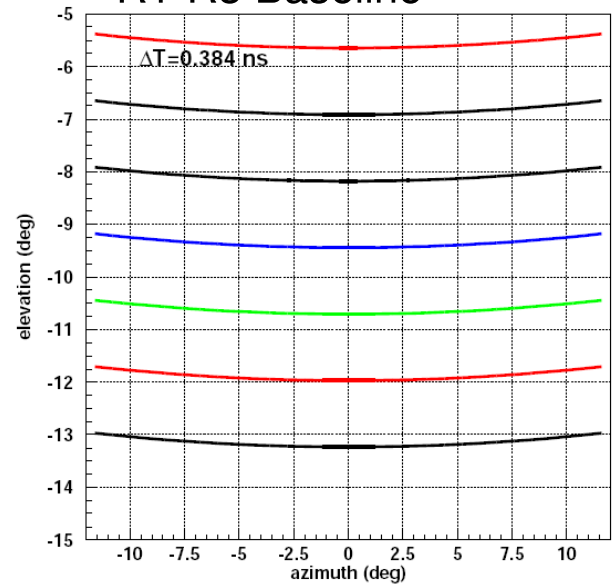
ANITA-3 Phi Sector Geometry



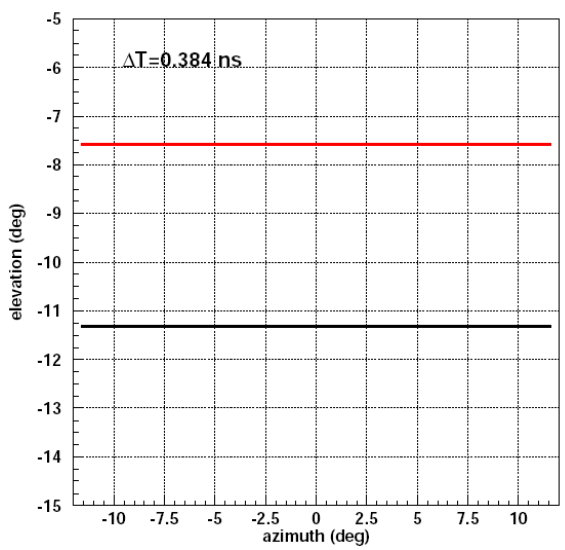
R1-R2 Baseline



R1-R3 Baseline



R2-R3 Baseline



$\Delta\theta$ with ΔT=0.384ns

R1-R2: 2.0°

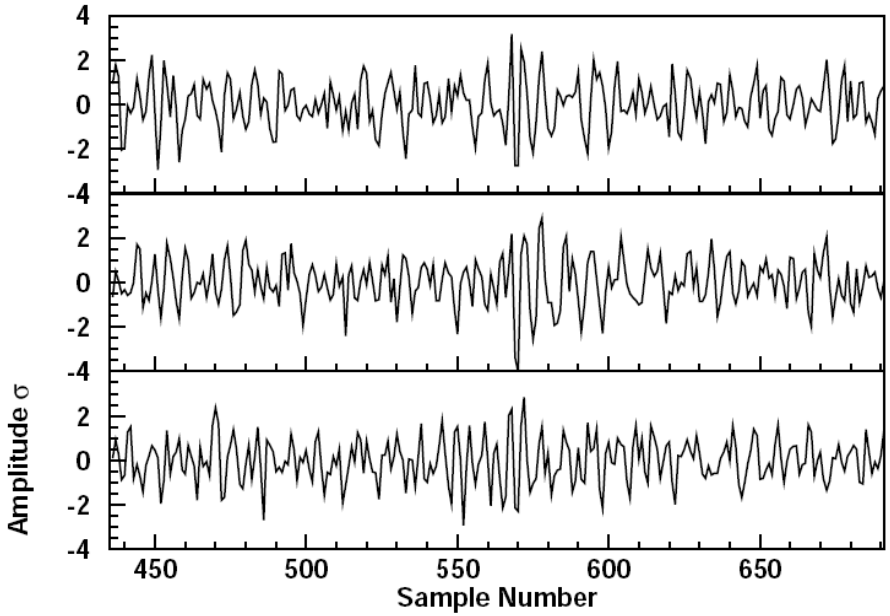
R2-R3: 3.9°

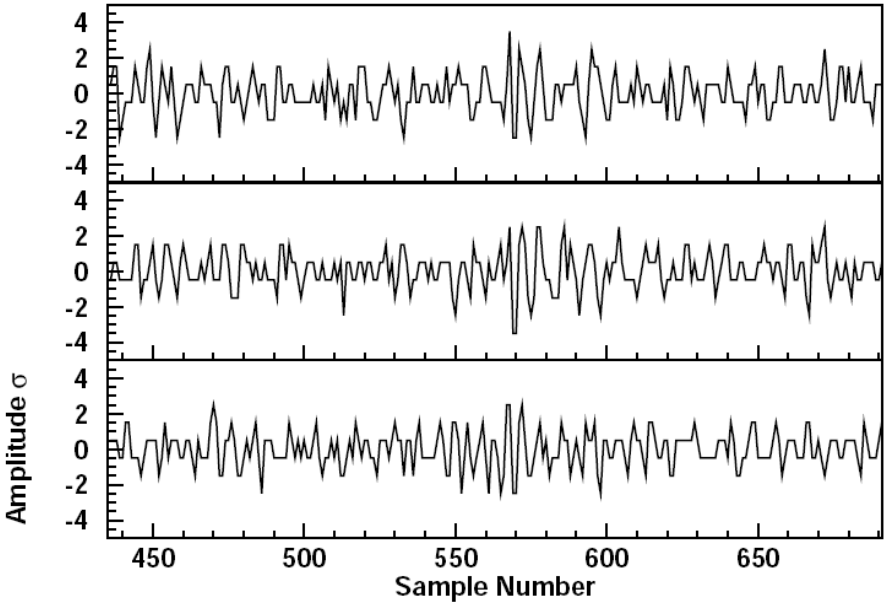
R1-R3: 1.2°

Trigger Simulation

- Produce 3 independent noise waveforms
- Inject the impulse response with the appropriate geometric delays
- 3σ input SNR example shown below

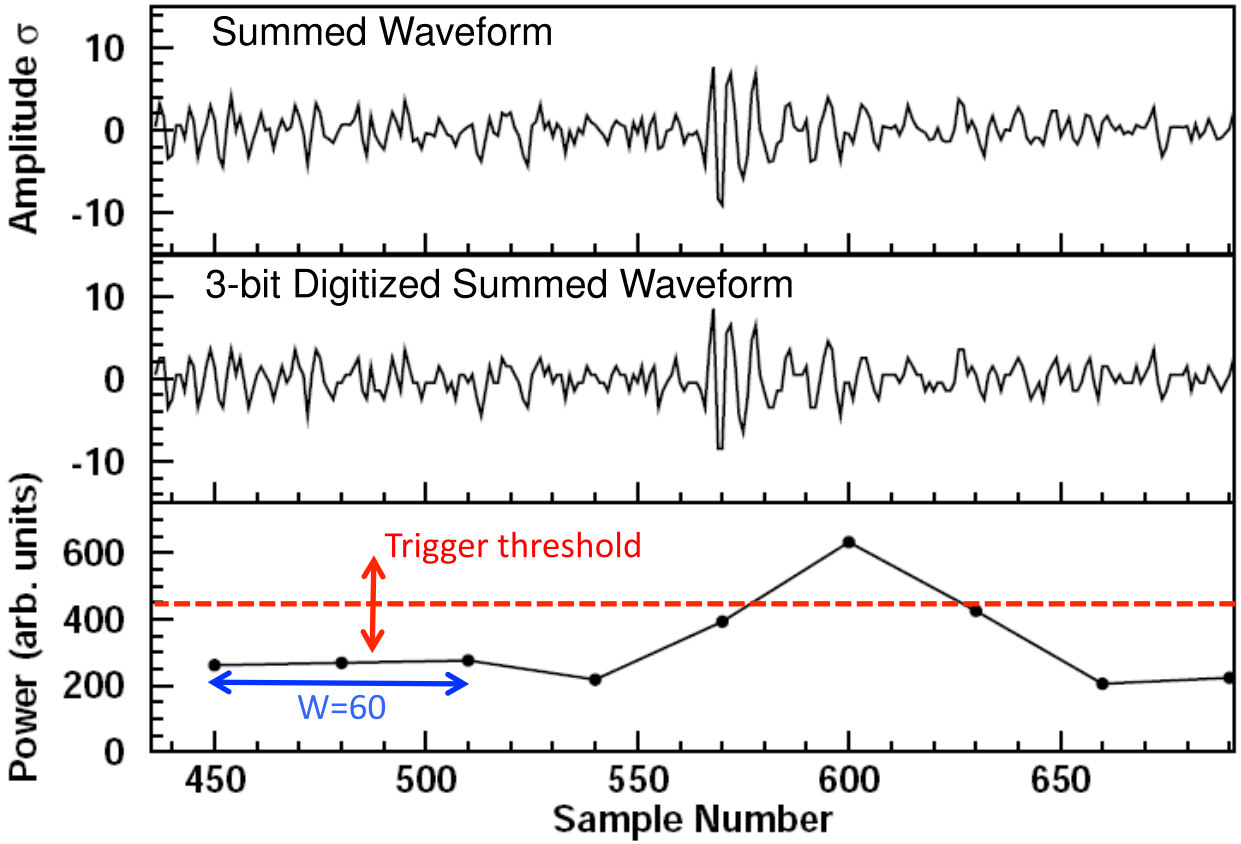
- Digitize waveforms with 3-bits, 8 levels
- Levels set at ±0.5σ, ±1.5σ, ±2.5σ, ±3.5σ





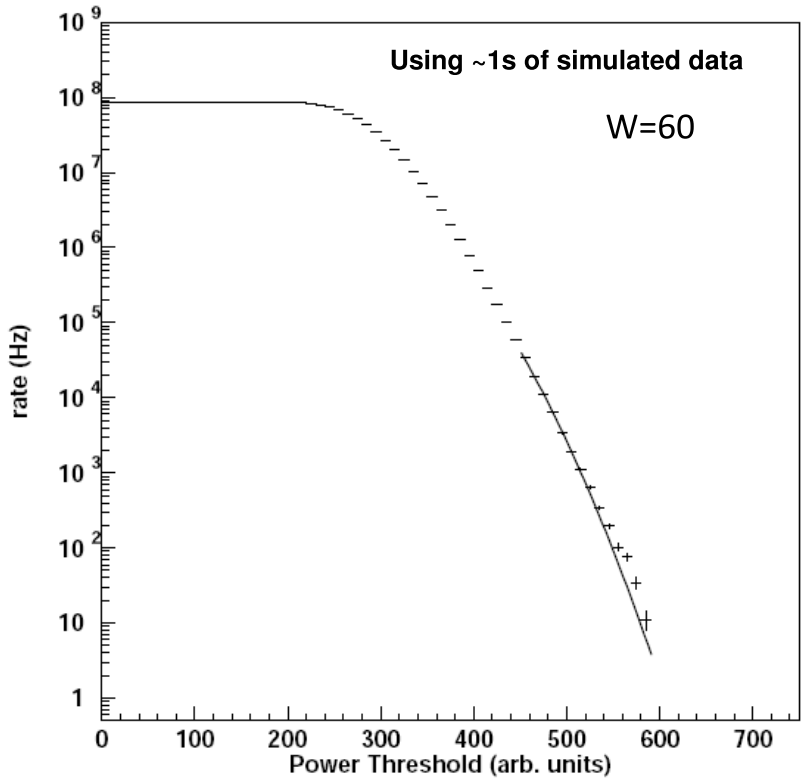
Coherent Sum Trigger

- Phase align the 3-bit digitized waveforms according to various θ (1° steps)
- Sum waveform and take a power over W samples.
- Repeat the operation every W/2 samples (interleaving).
- Trigger at a given coherently summed power level.

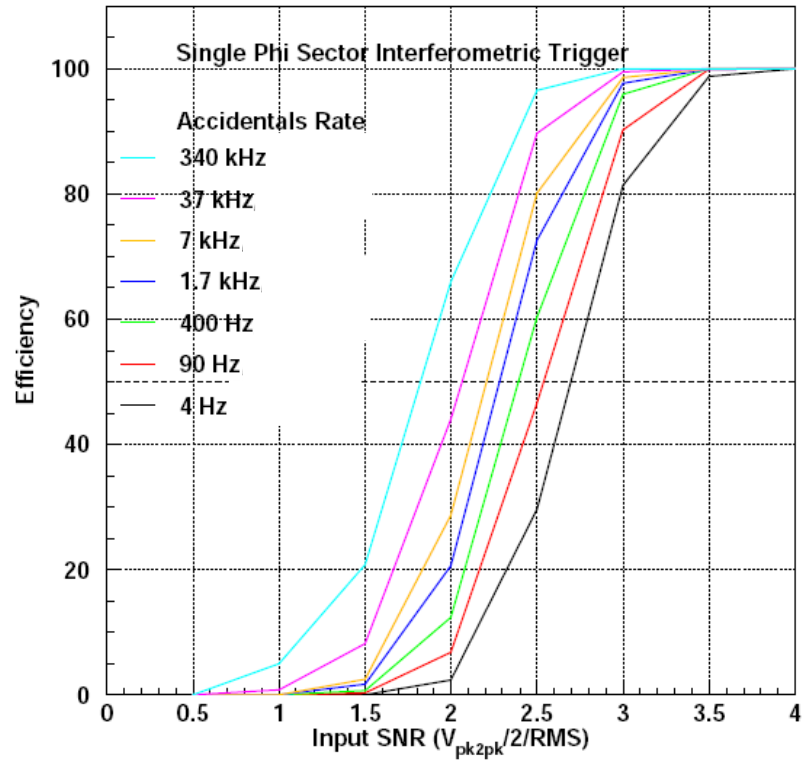


Single ϕ-sector Triggering Efficiency

Accidentals Rates



Triggering Efficiency Results



Set W=60 samples
(full length of impulse response)
for first study.

Rate	50% Efficiency SNR
400 Hz	2.40
90 Hz	2.55
4 Hz	2.70

Operations count

- 2.6 Gsa/s sampling
- 60 sample window
- 3 channels
- 60 angular scans
- Coherent additions additions and multiplications give

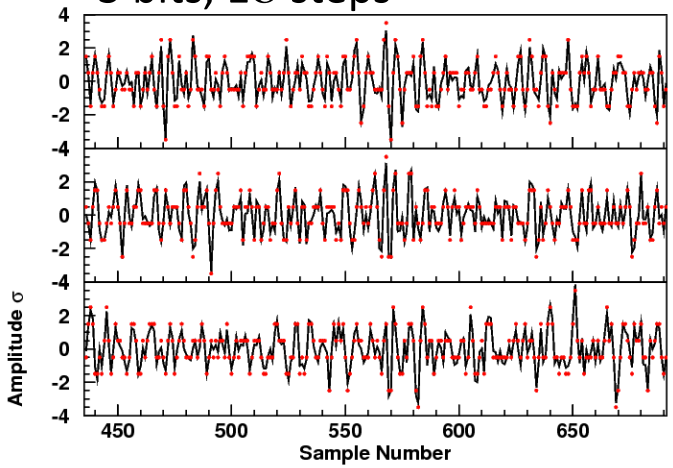
- Nops/s≈1.2×10^{12} ops/s

Quick and Dirty Power Estimate

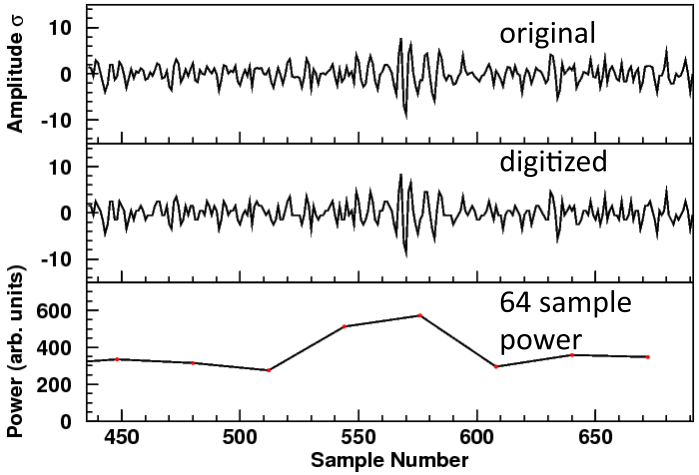
- For a CMOS process $\Delta E = C\,V\,\Delta V$ Joules per bit that changes
- $\Delta V \approx 1$ Volt
- $V \approx 1$ Volt
- <u>$C \approx 10$ femtoFarads</u>
- $\Delta E \approx 10^{-14}$ Joules / bit
- 9 bits/op (sum of 3 channels with 3-bit digitized signals, all 48 detector channels.
- 3.2 Watts total
- Current system uses about 50 W

Digitization Examples

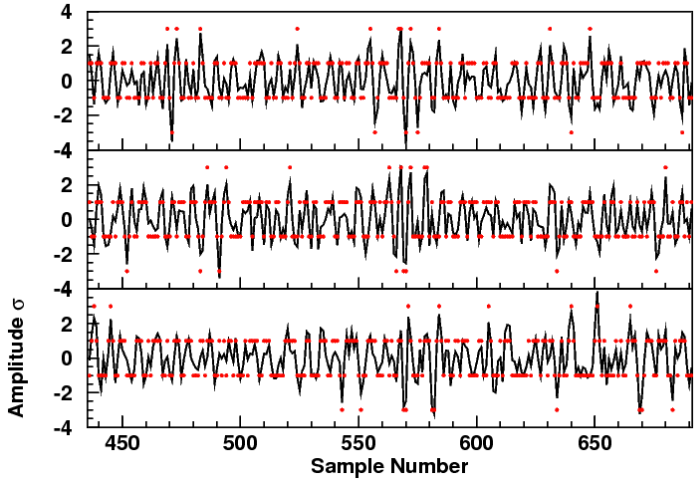
3 bits, 1σ steps

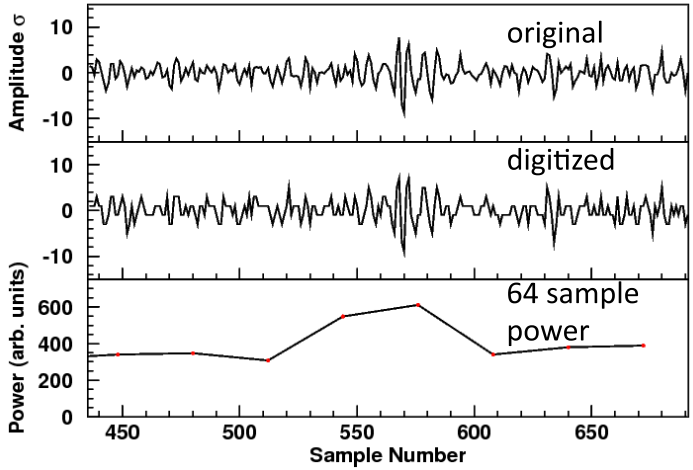


Coherently Summed Waveform



2 bits, 2σ steps





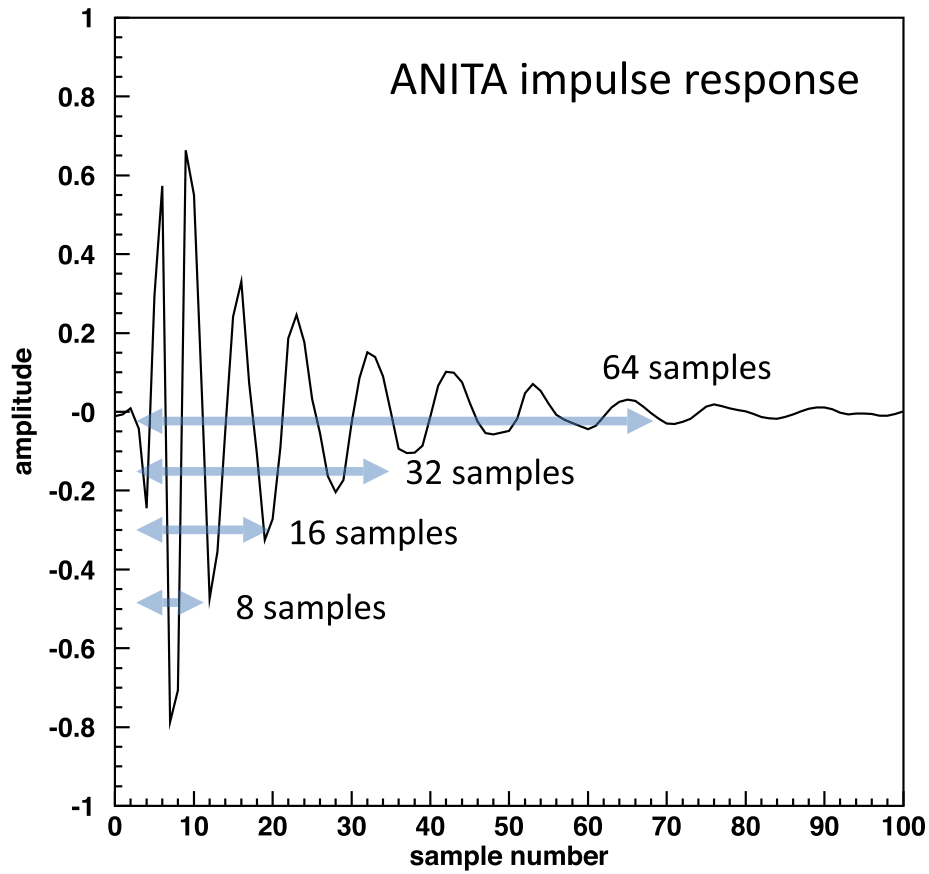
Digitization Variations

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

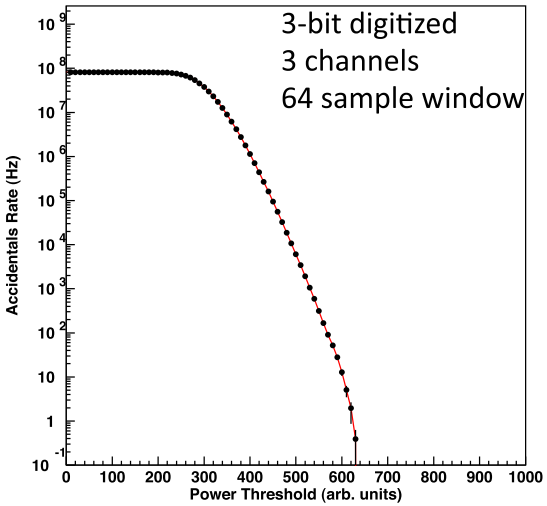
Parameters chosen for earlier studies are optimal.
2-bit digitizers do not look like such a bad alternative if need be.

Integration Time Window

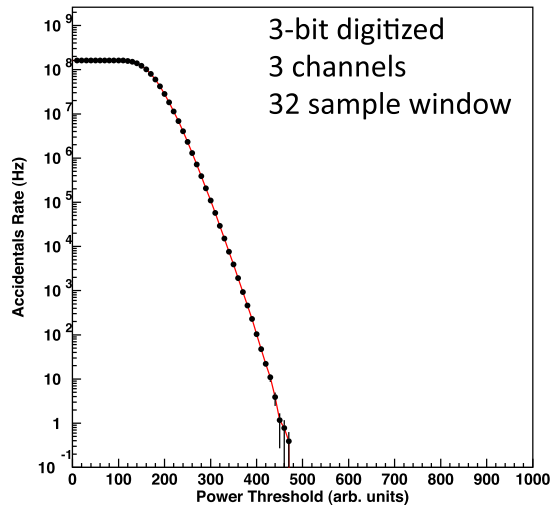
Integrate the power over a given time window W.



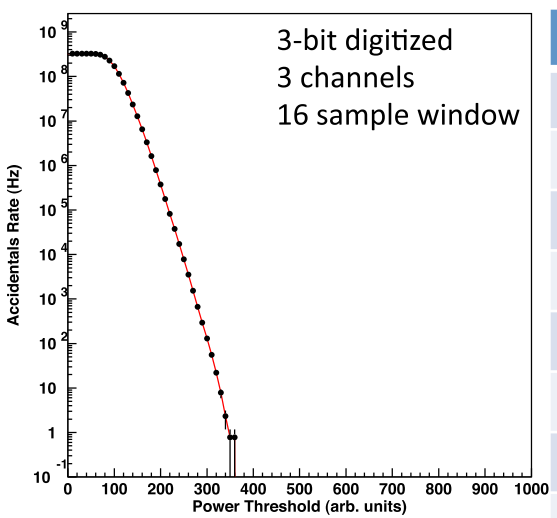
Single Phi-sector Accidentals Rates



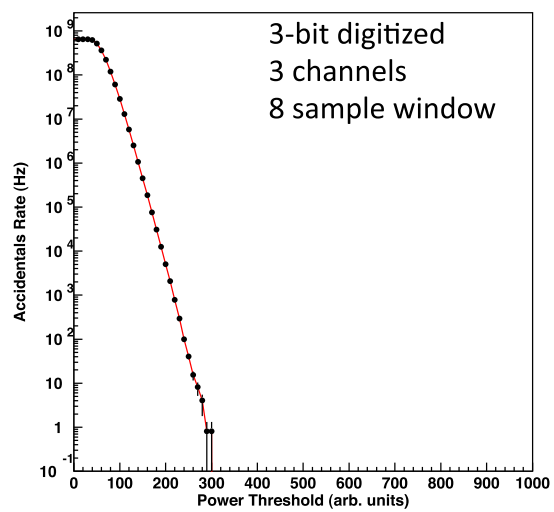
Rate (Hz)	Thresh.
10^7	347
10^6	402
10^5	447
10^4	490
10^3	528
10^2	565
10	602
1	623



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



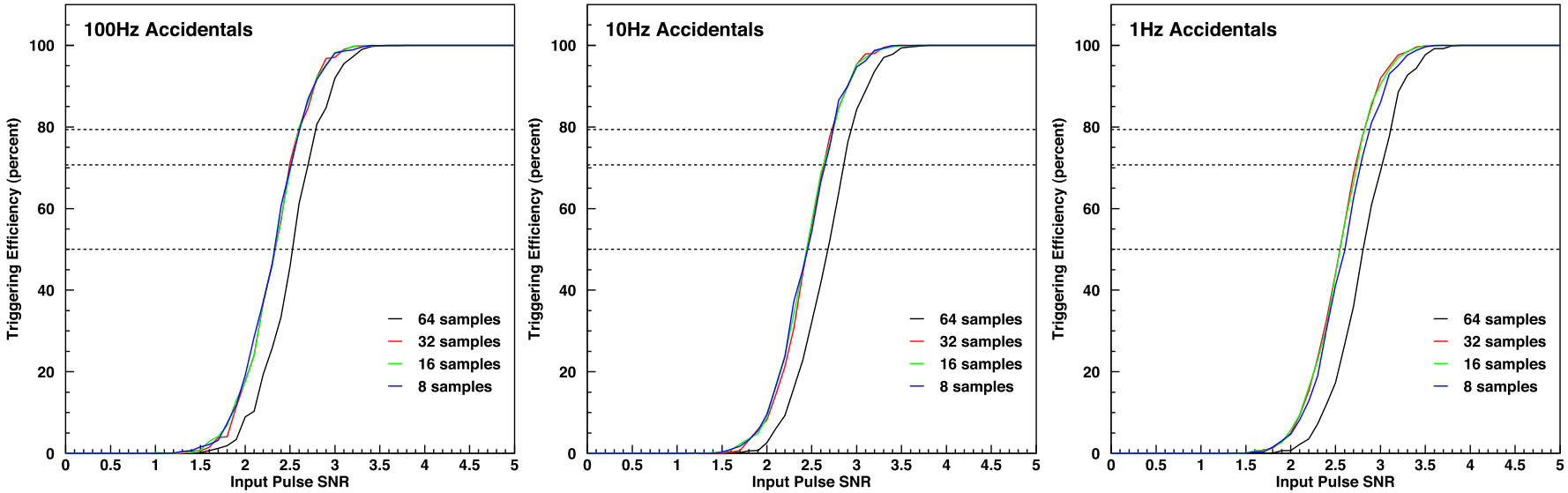
Rate (Hz)	Thresh.
10^7	152
10^6	185
10^5	216
10^4	245
10^3	278
10^2	303
10	327
1	348



Rate (Hz)	Thresh.
10^7	112
10^6	139
10^5	166
10^4	192
10^3	216
10^2	239
10	260
1	287

Integration Time Window on Trigger Efficiency

For various single ϕ-sector accidentals rates



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.

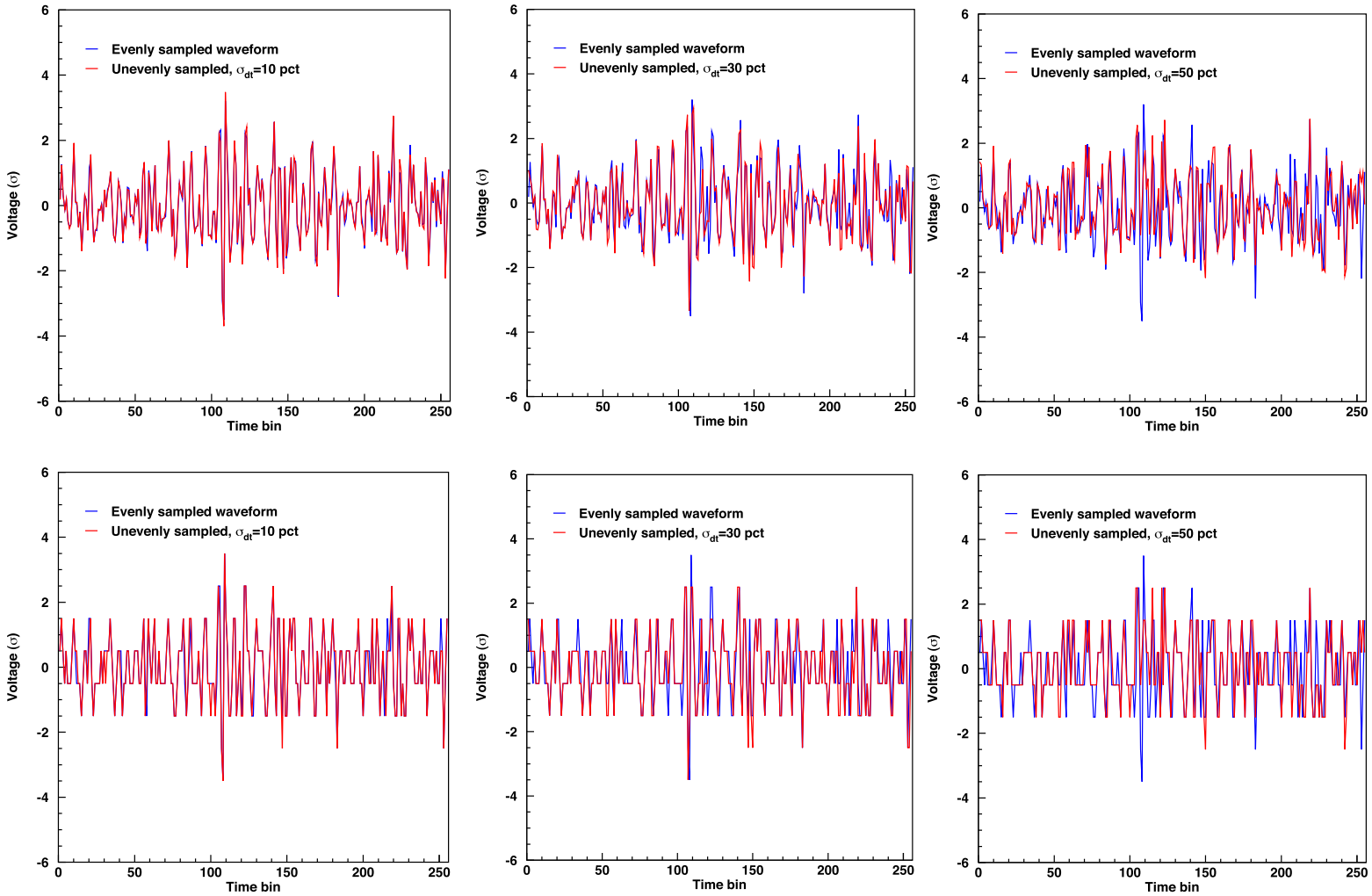
Time sample variance = 10%

Time sample variance = 30%

Time sample variance = 50%

Waveforms

3-bit digitized waveforms



Unevenly sampled summed waveform examples.

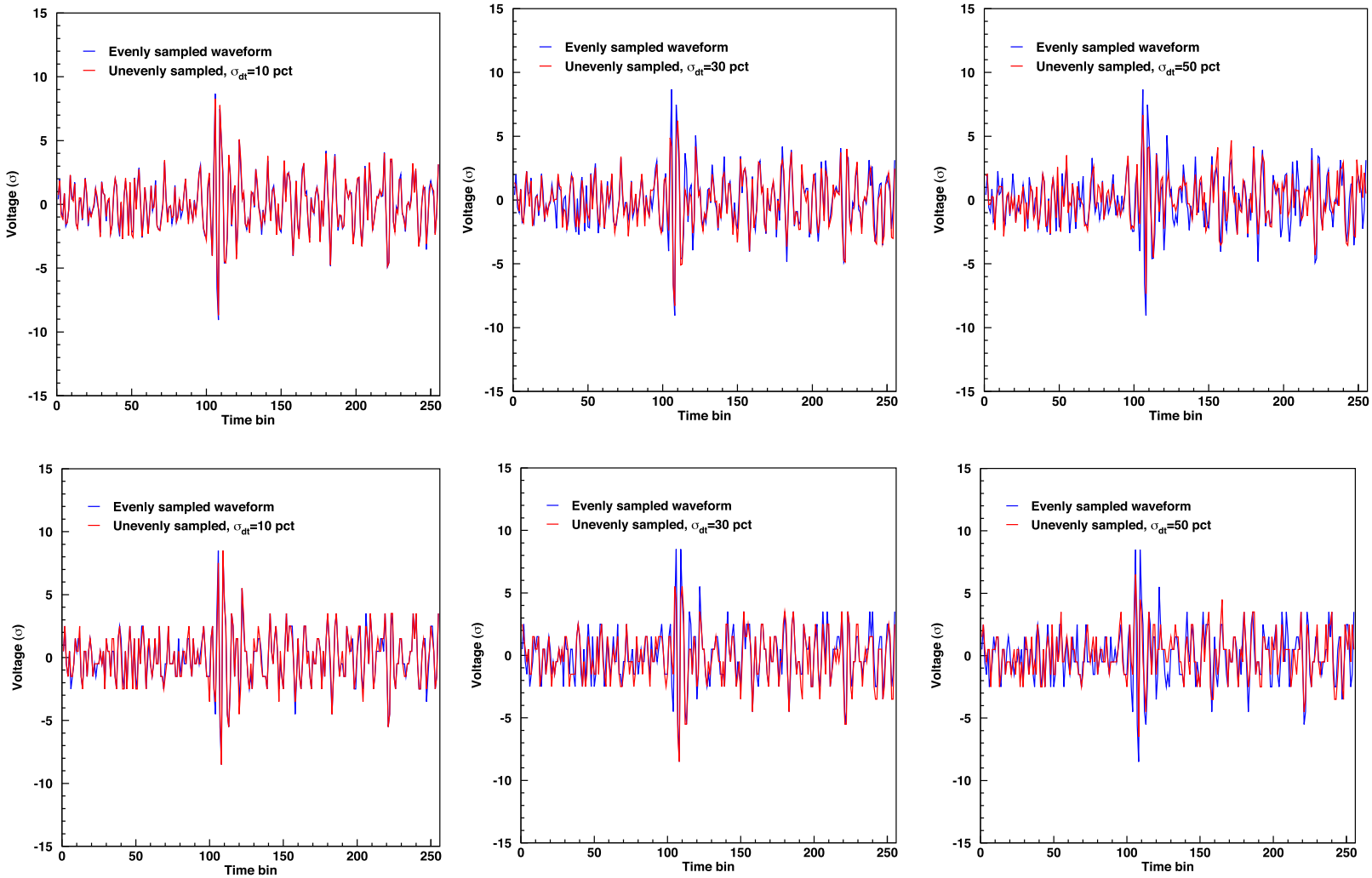
Time sample variance = 10%

Time sample variance = 30%

Time sample variance = 50%

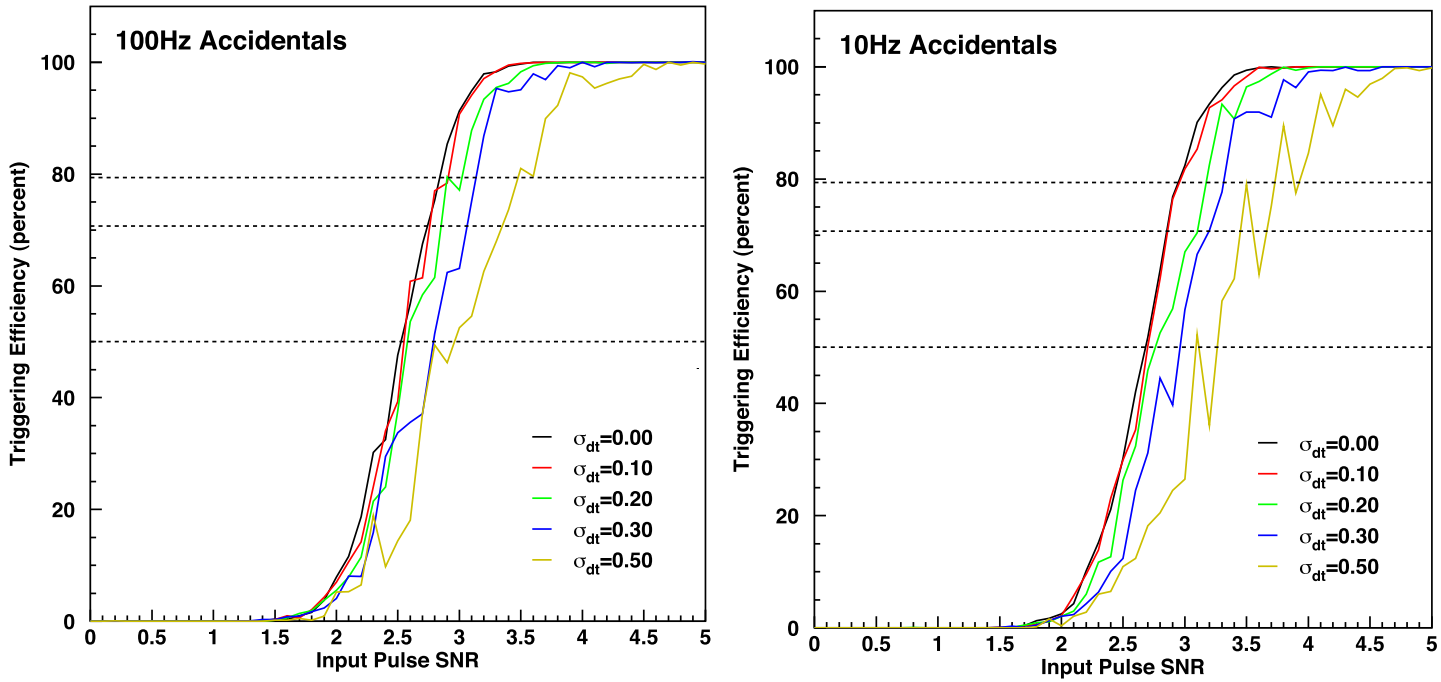
Coherently Summed waveforms

Coherently summed 3-bit digitized waveforms



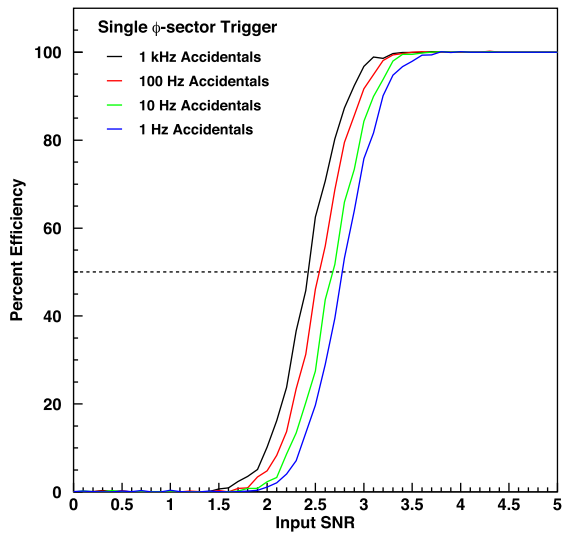
Uneven Timing Effect on Trigger Efficiency

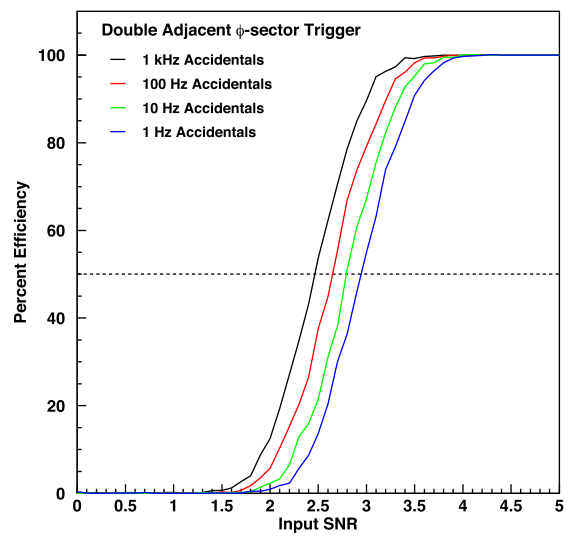
For various single ϕ-sector accidentals rates

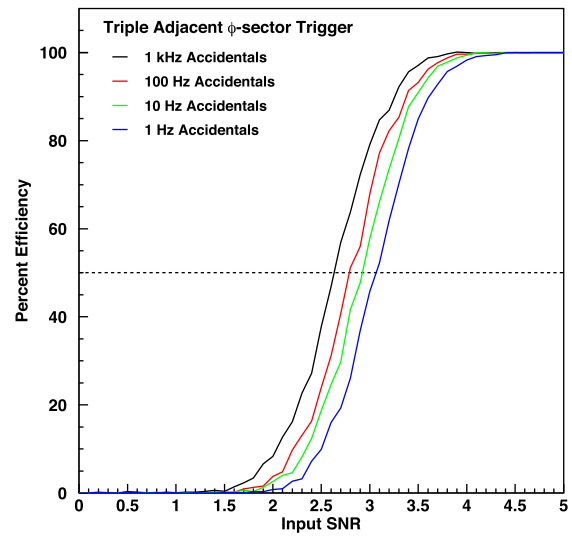


ANITA data recording digitizers, built with the same process, have ≤ 15% sample timing variance.

Trigger Efficiencies Using Coincidence Triggers







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

Simulation Scenarios That Improve the Coherent Waveform Sum Trigger Efficiency

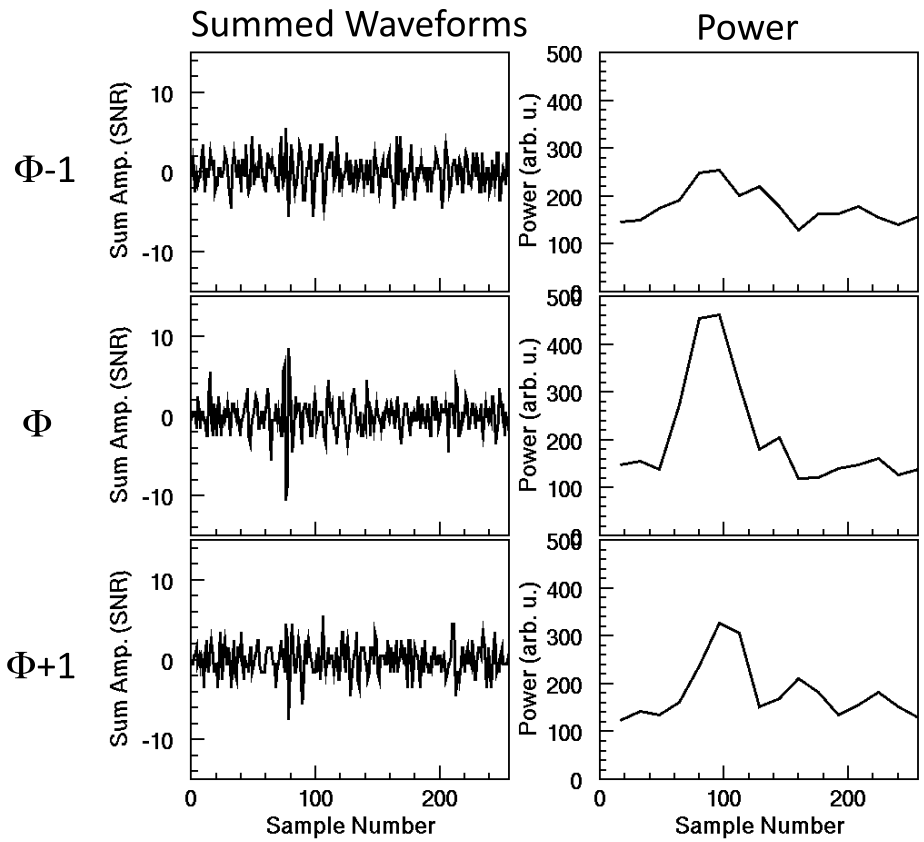
- **Power Sum:** Every 16 samples (6.15 ns) each phi-sector produces a maximum power readout of the waveform sum scanning various elevation angles. Trigger on the summed power.

- **Sum of sums:** Rather than summing the power, each phi-sector transmits the coherently summed waveform corresponding to the maximum power. These are coherently summed and the trigger decision is made on the power.

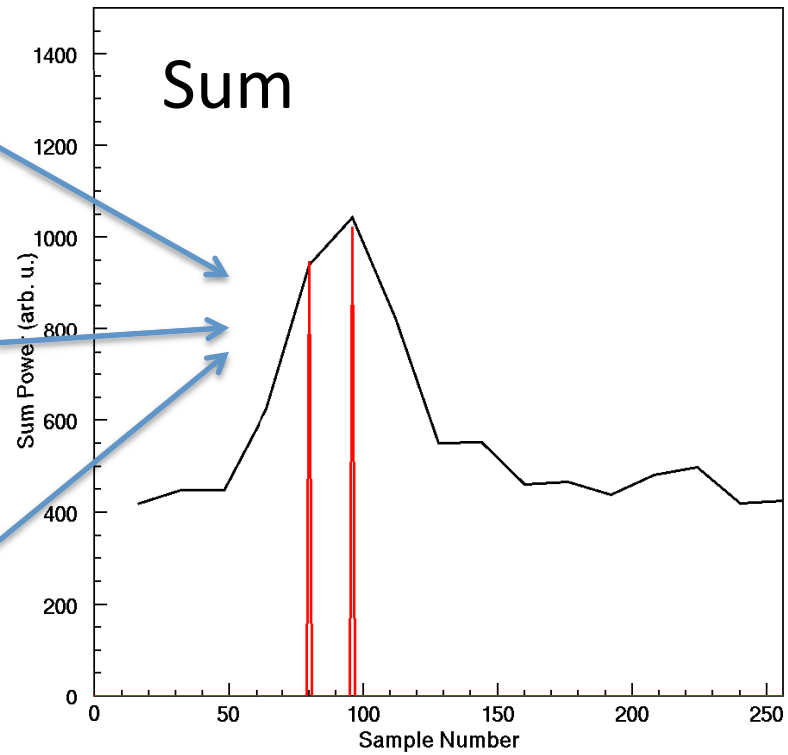
- **Full coherent sum:** This takes a set of phi-sectors and tests computes the power of the coherent sum of all waveforms over all relevant elevation and azimuth angles.

Power Sum Trigger: Example

Injected SNR=2.3

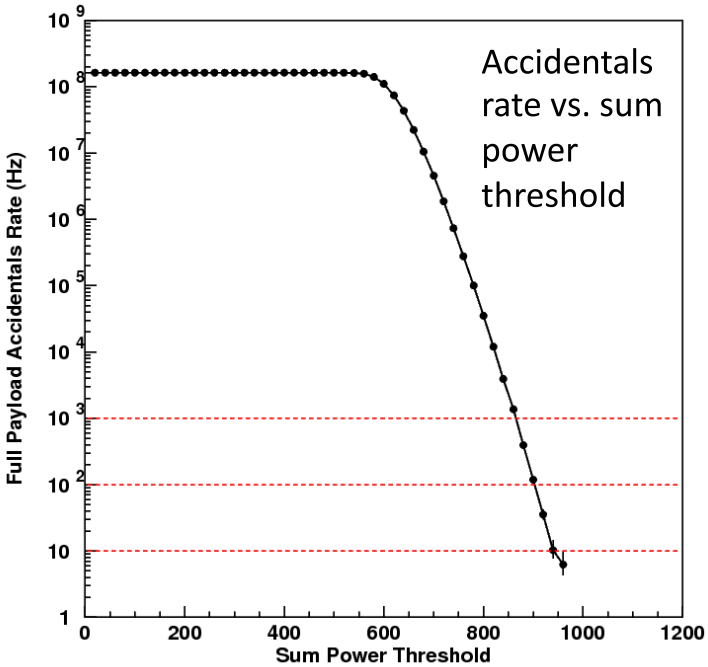


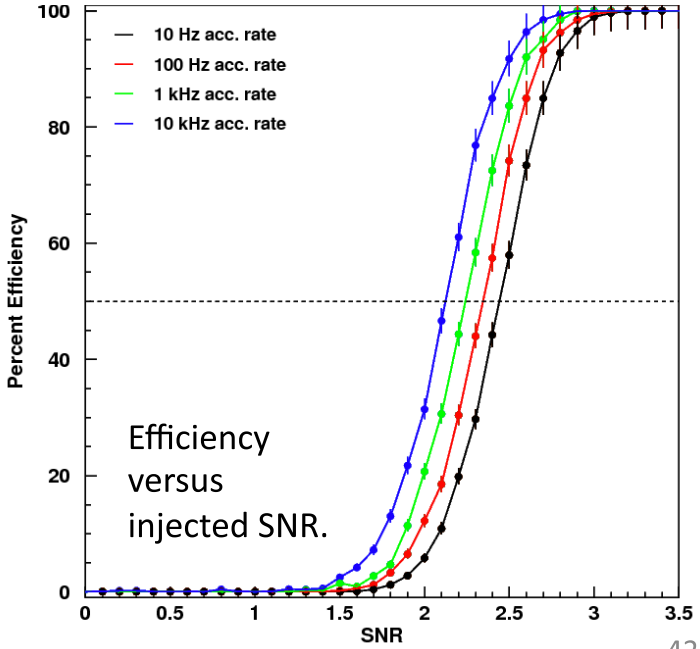
Threshold at sum power=900



Power Sum Trigger : Results

Full Payload Acc. Rate	50% SNR
10 Hz	2.45
100 Hz	2.32
1kHz	2.24
10 kHz	2.11
100 kHz	1.97
1 MHz	1.80



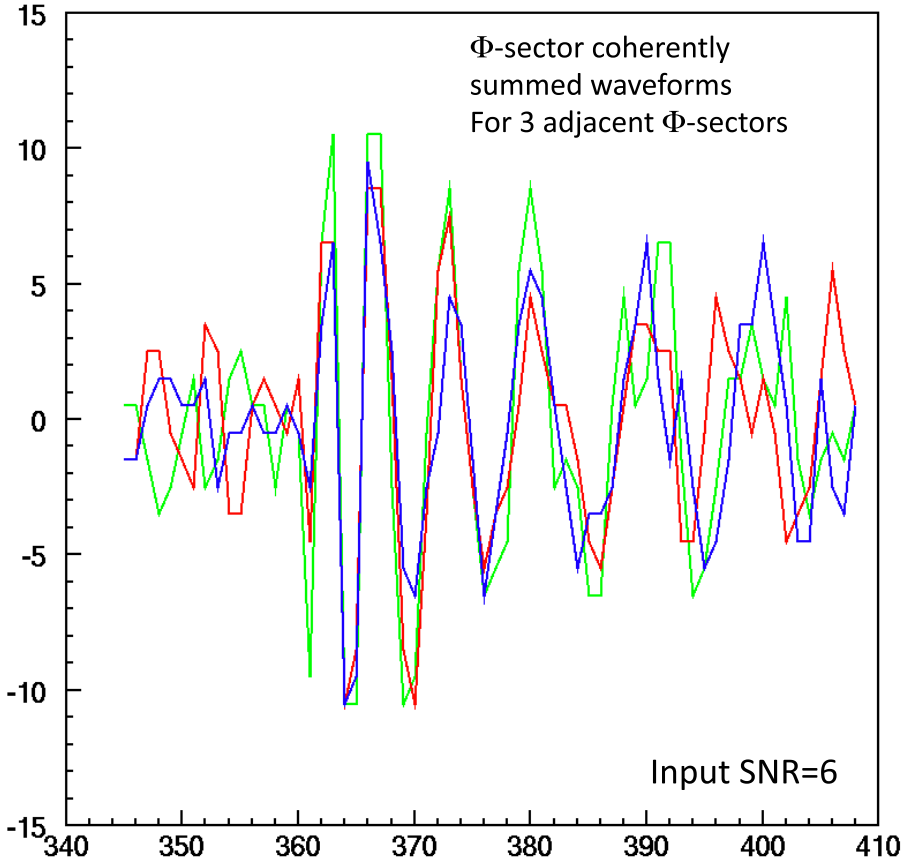


Sum of Sums Trigger : Example

1. Run the single Φ-sector coherent waveform sum.

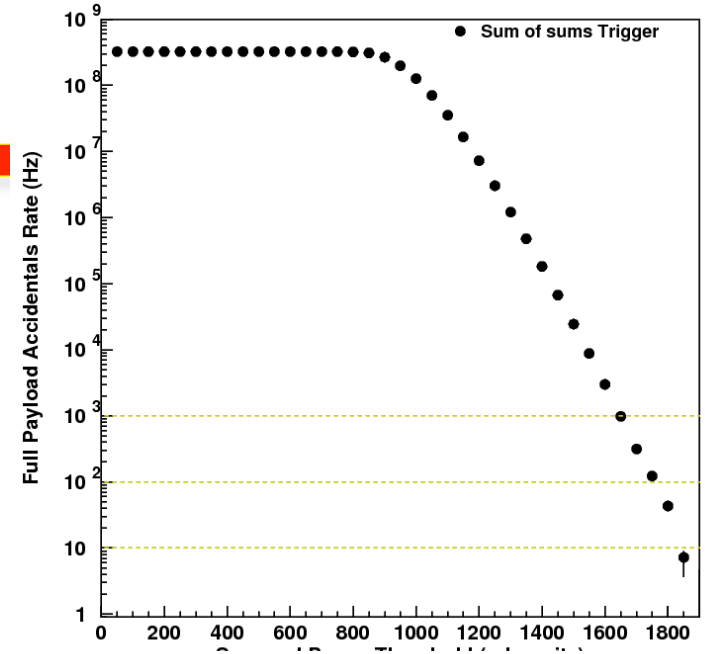
2. Record the summed waveform corresponding to the elevation angle that results in the highest amount of coherent power in each Φ-sector.

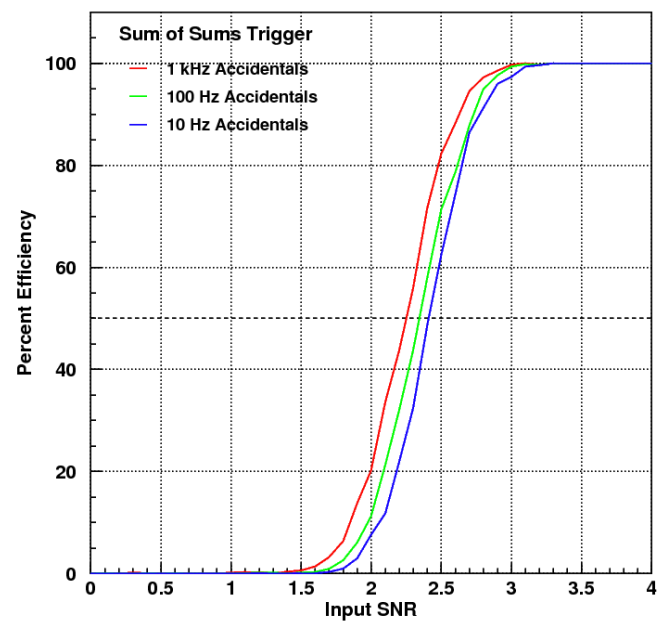
3. Output these waveforms to a second level coherent sum trigger. Need to scan several combinations of elevation and azimuth to account for all possible alignments. ~200.



Sum of Sums Trigger: Results

Acc. Rate	50% Eff. SNR
1kHz	2.25
100 Hz	2.32
10 Hz	2.41



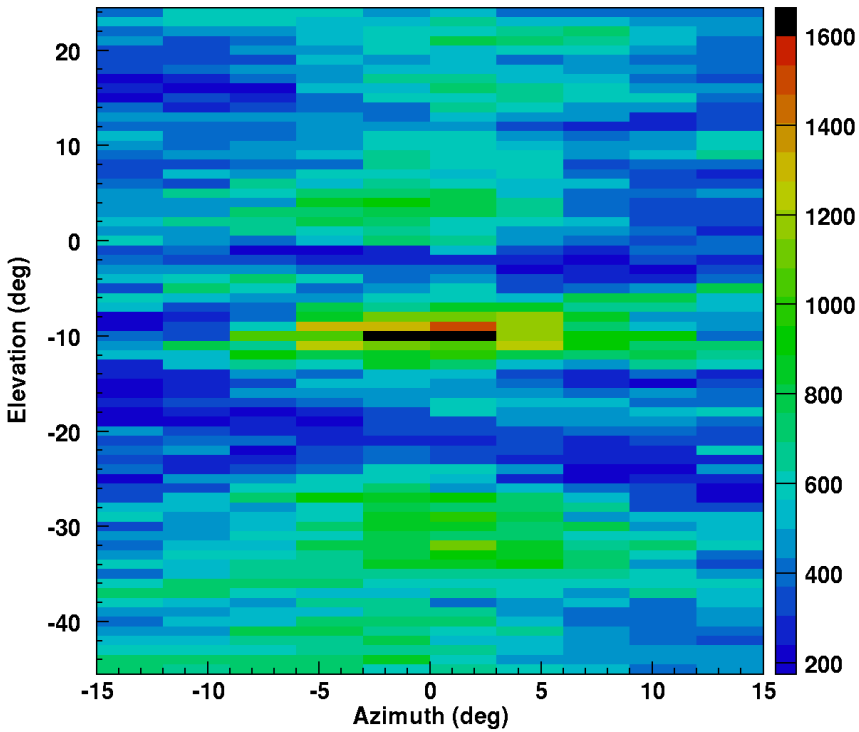


Results are practically the same as simply adding the power of the adjacent phi-sector coherent sums.

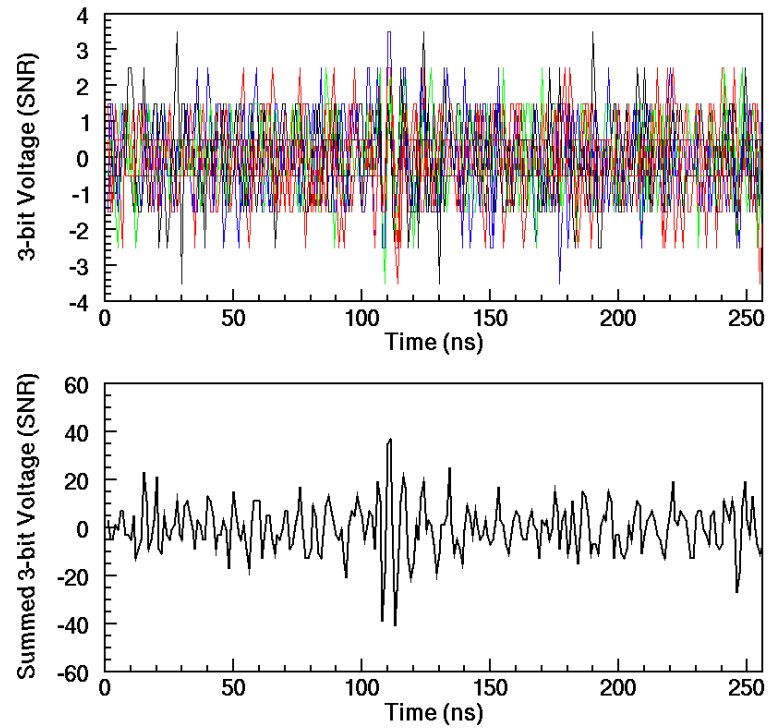
Increased trials factor reduces sensitivity (phi directions need to be scanned in order to make this work).

Full Coherent Sum Trigger : 3 Φ-sector Sum Trigger Example

SNR=2.0σ injected waveform



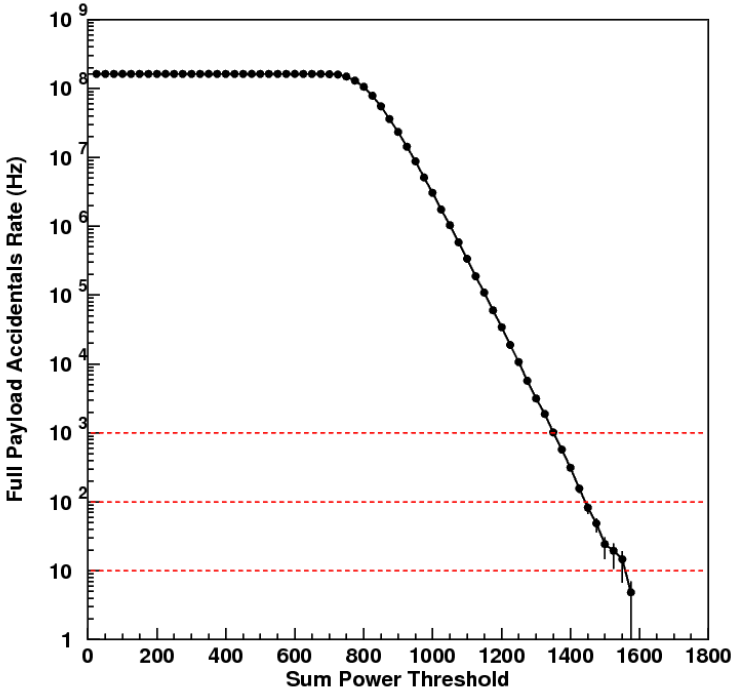
$\Delta\theta$=1 deg x $\Delta\phi$=3 deg power map

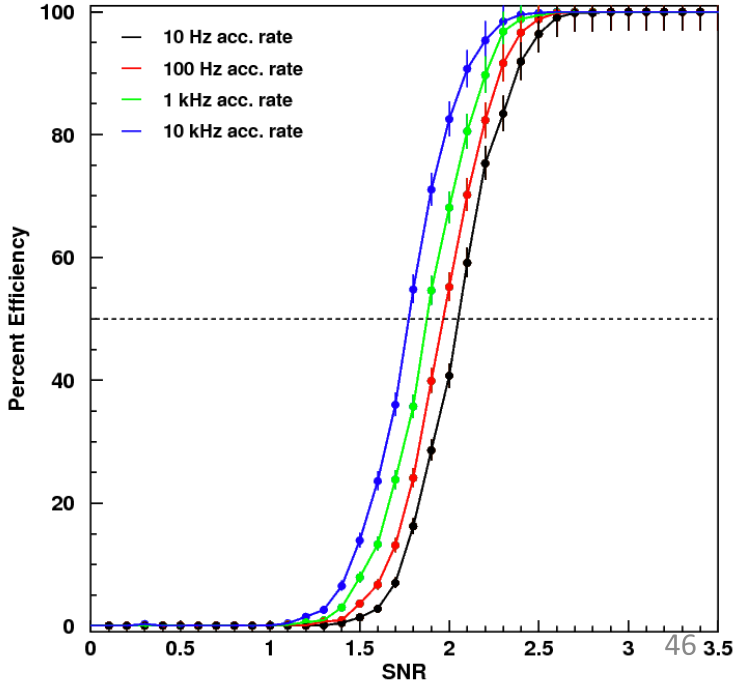


Full Coherent Sum Trigger: 3 Φ-Sector Results

Full Payload Acc. Rate	50% SNR
10 Hz	2.05
100 Hz	1.96
1kHz	1.90
10 kHz	1.80

Vastly improved results. However, the operations count increases by an order of magnitude not to mention the amount of data that needs to be shuffled around in the ASIC.





Summary of Results

Trigger Type	50% Eff. SNR at an Accidentals rate of 100 Hz
Tunnel Diode (This simulation)	2.87
Tunnel Diode (Prior simulation)	2.7
Single Phi-Sector Trigger	2.5
Power Sum	2.32
Full coherent sum (3 Φ-sector)	1.96

Full coherent sum gives best results at the cost of added complexity.

Due to development schedule constraints the power sum option was selected.

3-bit Digitizer Development

RITC
Realtime Independent Three-bit Converter

First version has been fabricated.
Currently undergoing testing at the University of Hawaii.
~52 mW power consumption.
~ 2 Watts for all ANITA channels.

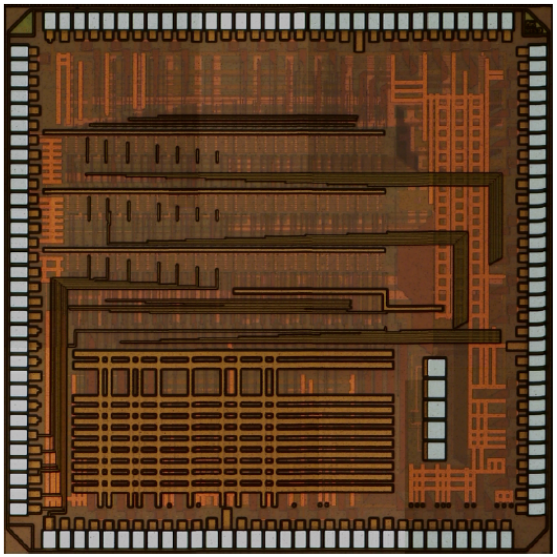


Fig. 4. Die photograph of RITC, as fabricated. The die size is 3.13×3.13 mm^2.

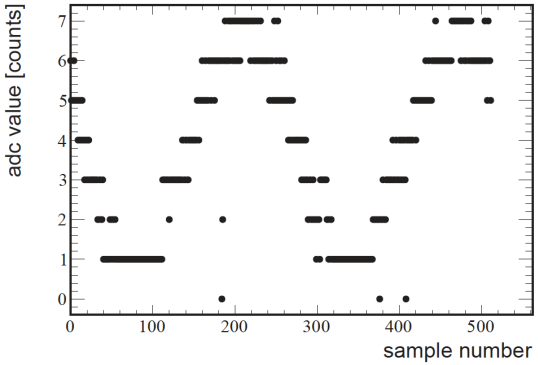


Fig. 13. A 2 MHz sine wave, as digitized into 3-bits by RITC at a sampling rate of approximately 510 MSa/s. Comparator threshold levels are chosen to be roughly uniformly spaced near the region of minimum comparator nonlinearity.

<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]

arXiv:1203.4178

Correlator Development

GLITC

Gate Logic Implementation of Trigger Correlator

- Algorithm was successfully implemented in an FPGA and submitted for ASIC fabrication.
- Expect to receive at at the University of Hawaii this month.

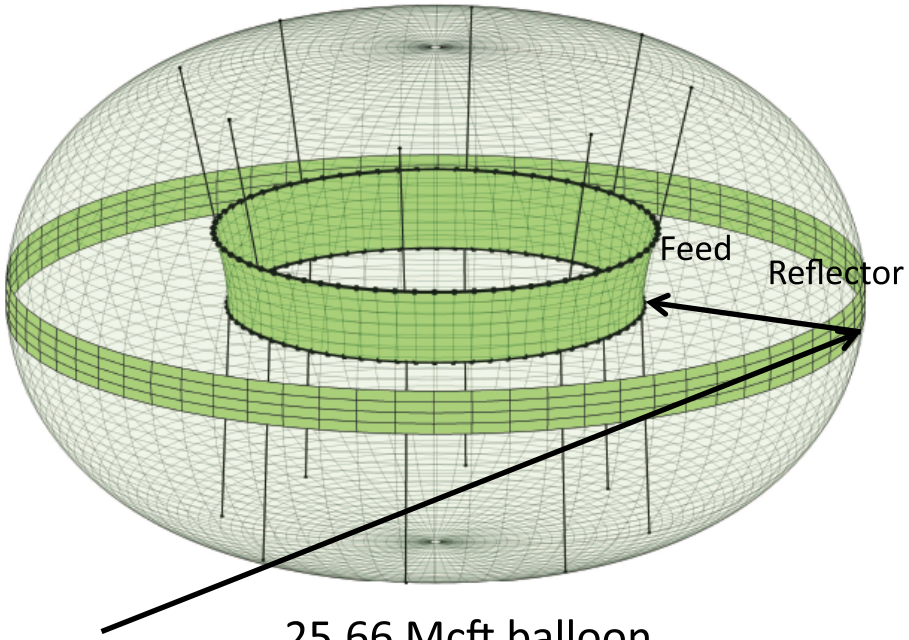
Future Experiments

ExaVolt Antenna – EVA

Uses the balloon structure itself to provide a high gain reflector antenna.

Reflectors provide factors of 10-100 improvement over ANITA.

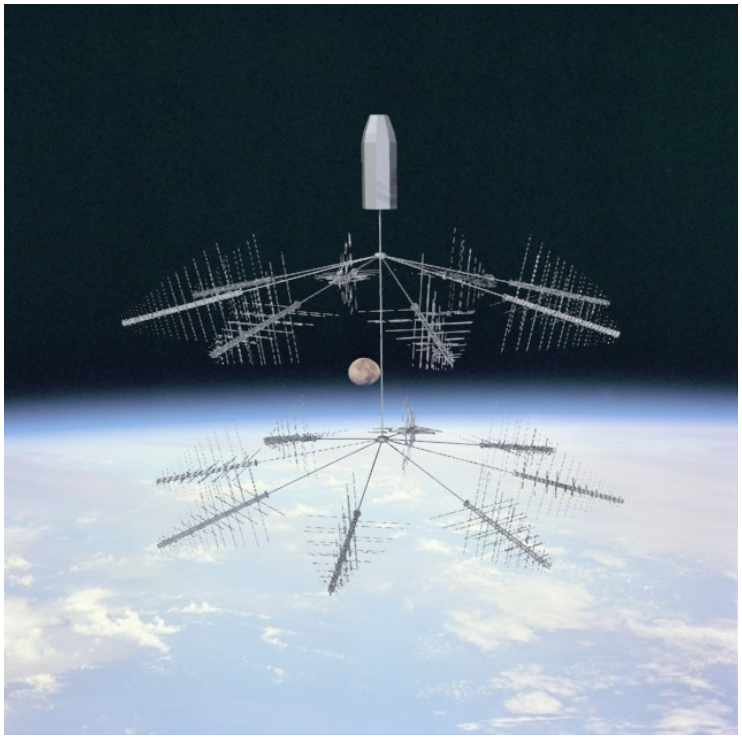
Currently funded for a scaled proof of concept prototype.

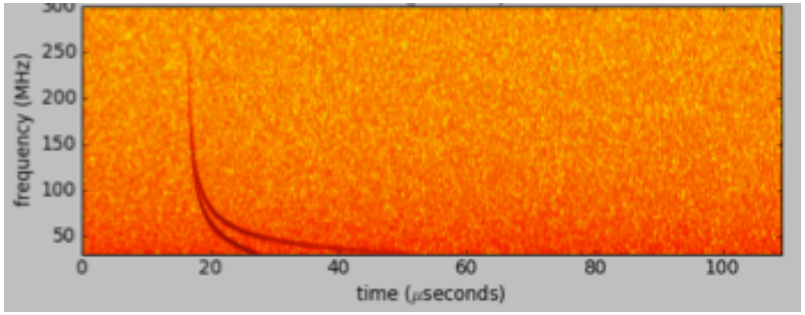


BZ neutrino models	*Events, ANITA-II, 28d*	*Events, EVA, 50d*	*ratio, EVA/ANITA*
Mixed UHECR composition [30]	0.05	5.0	100
Minimal, no evolution [3, 32, 33]	0.3-0.9	9.2-38	~ 40
$\Omega_m = 0.3, \Omega_\Lambda = 0.7$, Standard model [3]	0.7	29	41
Waxman-Bahcall E^{-2} flux (minimal) [34]	0.49	6.5	13
GRB UHECR-sources [46]	1.44	66	46
Strong source z-evolution [3, 31, 33]	2.2-5.3	40-60	11-18
Maximal, saturate all bounds [31, 33]	16-25	180-220	~ 10

Future Experiments

- Synoptic Wideband Orbiting Radio Detector (SWORD)
- "ANITA" from space.
- Detection of UHECRs with $>10^{20}$ eV at a rate of hundreds per year.
- Charged particle astronomical observatory.
- Requires realtime de-dispersion for triggering.
- Algorithms currently being developed in an Innovative and Spontaneous Concepts RTD study.
- Low resolution realtime digital techniques will be mission enabling.





Conclusions

- Realtime low power digital triggering techniques provide higher sensitivity to radio detection experiments.

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

Backup Slides

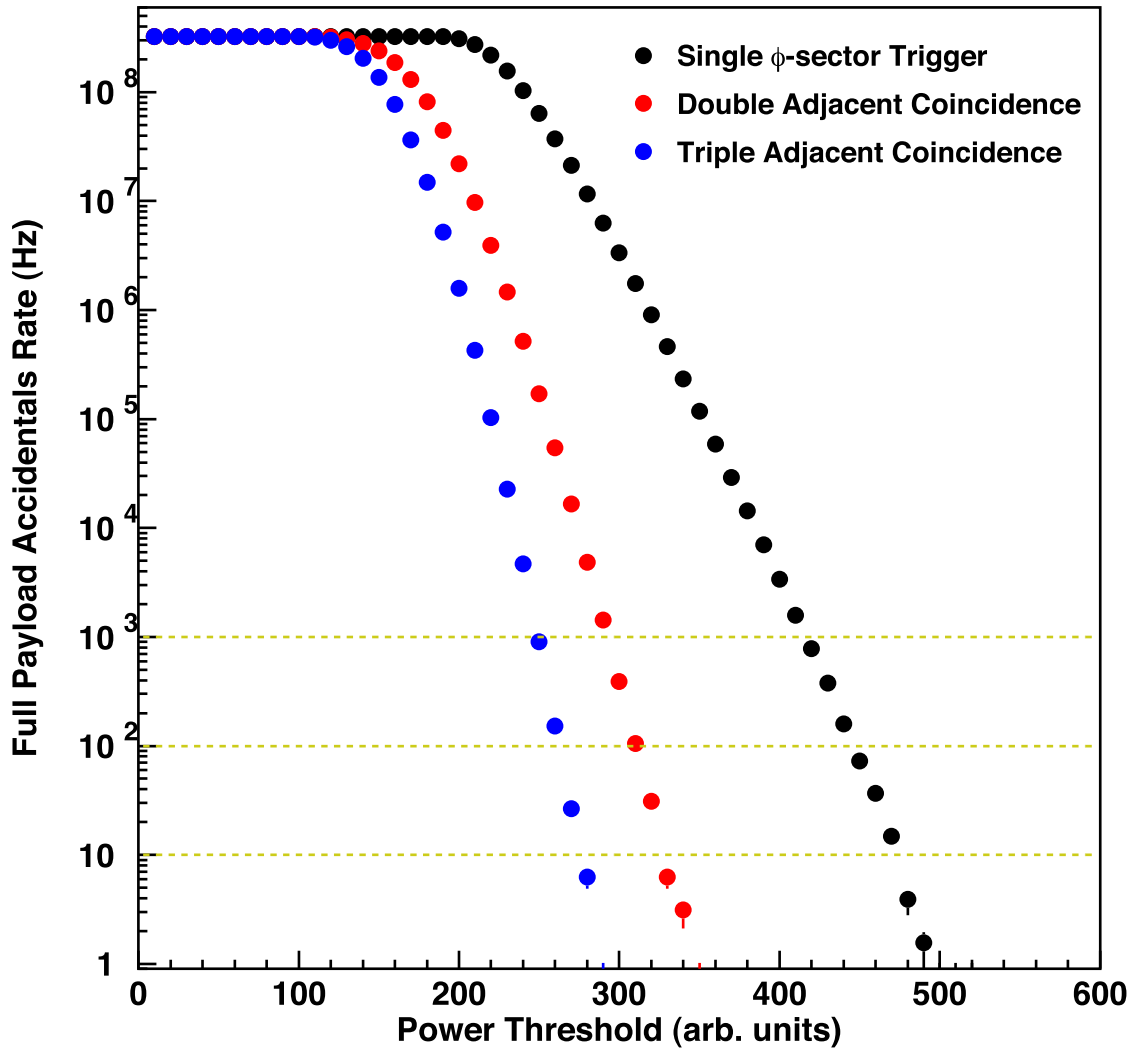
Full Payload Accidentals Rates

-16 ϕ-sectors × 2 polarizations
-Rates dramatically reduced by coincidence requirements

-10 Hz: The rate ANITA-2 can handle

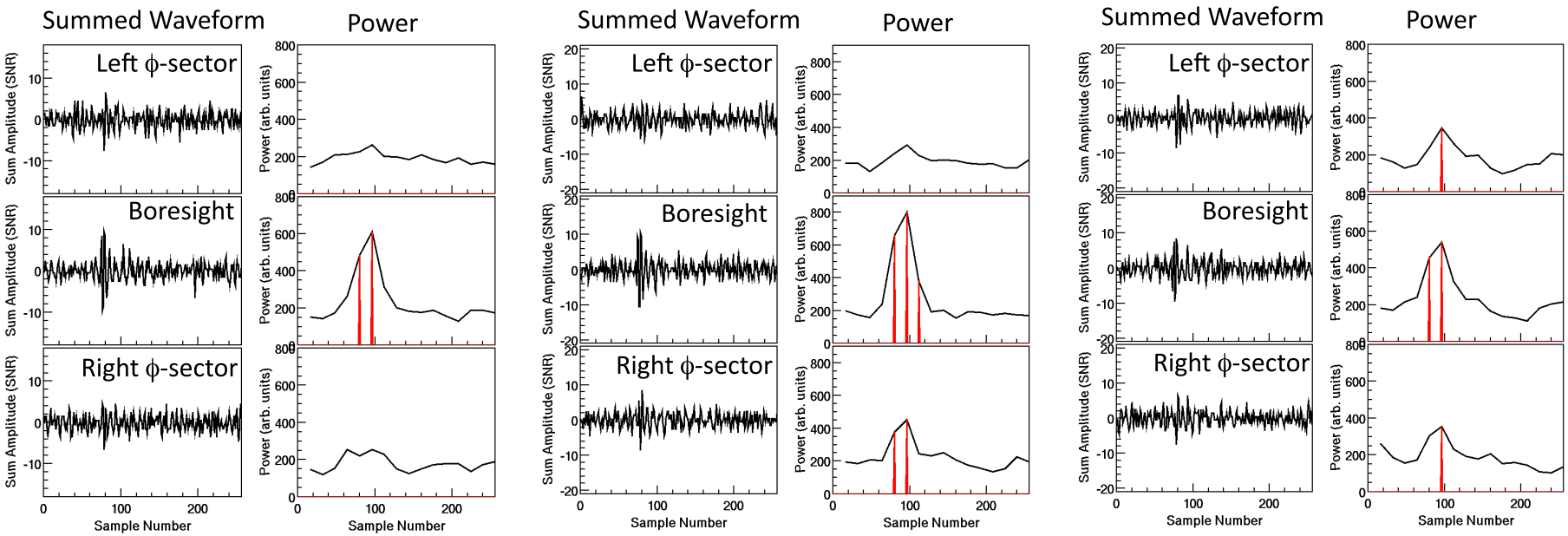
-100 Hz: the rate a software interferometer could handle (with quite a bit of work).

-1kHz: max rate the SURF can handle. A hardware interferometer could be used.



Coincidence Trigger Examples

3-bit digitization
32 sample integration window
10 kHz Single f-sector accidentals rate
3.3 input SNR waveforms on boresight.



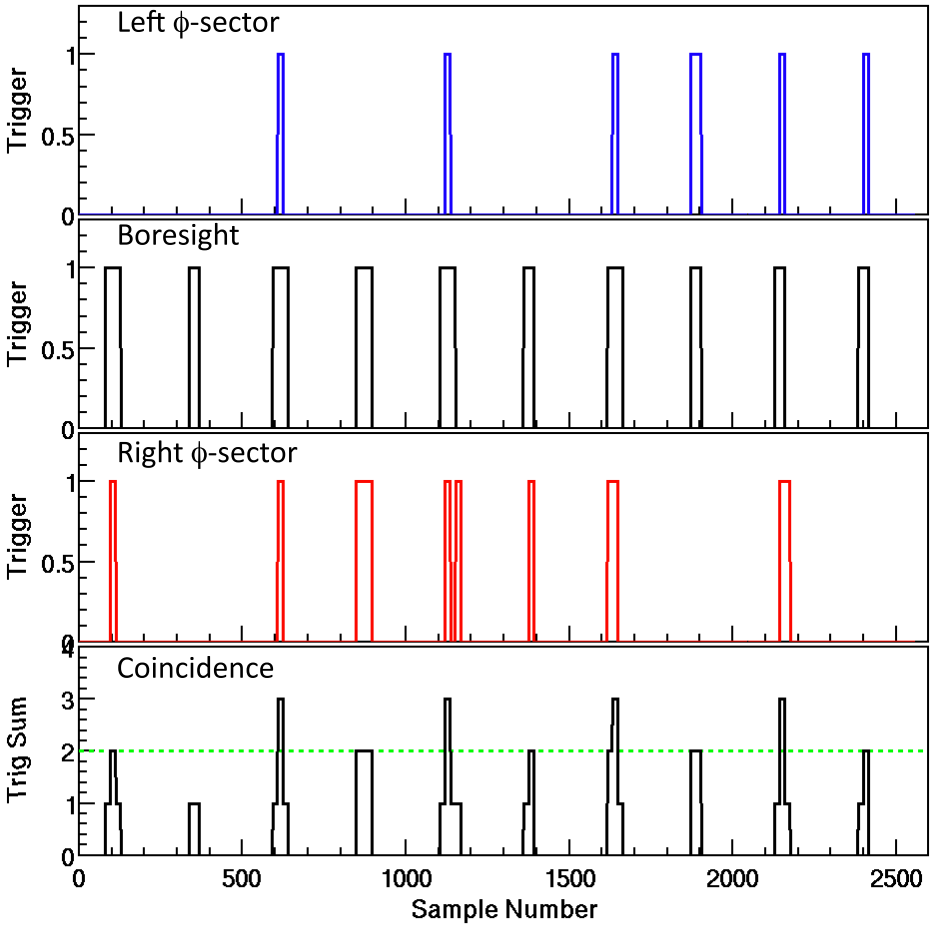
Coincidence Trigger Examples

Same conditions as previous slides.

3-bit digitization
32 sample integration window
10 kHz Single f-sector accidentals rate
3.3 input SNR waveforms on boresight.

The trigger and coincidence pattern are shown for 10 waveforms.

2 out of 3 coincidence maintains a fairly high efficiency.



Power Trigger (1): Computation

Scan every 16 samples (6.2 ns).

For each Φ-sector

For each elevation angle θ=+35,…,-45

Delay align the signals in 3 antennas and take the sum $\Sigma wfm_{\Phi}(\theta)$.

Take the power $P_{\Phi}(\theta)$ of $\Sigma wfm_{\Phi}(\theta)$ over 32 samples (12.3 ns).

Find the maximum power $maxP_{\Phi}=max\{P_{\Phi}(\theta)\}$.

Take $sumP_{\Phi}=maxP_{\Phi-1}+maxP_{\Phi}+maxP_{\Phi+1}$
Trigger on $sumP_{\Phi}$ if $sumP_{\Phi}$ > threshold

Sum of Sums Trigger (1): Computation

Scan every 16 samples (6.2 ns).

For each Φ-sector

For each elevation angle θ=+35,…,-45

Delay align the signals in 3 antennas and take the sum $\Sigma wfm_{\Phi}(\theta)$.

Take the power $P_{\Phi}(\theta)$ of $\Sigma wfm_{\Phi}(\theta)$ over 32 samples (12.3 ns).

Find the maximum power $maxP_{\Phi}=max\{P_{\Phi}(\theta)\}$.
Hold the corresponding $\Sigma wfm_{\Phi}(\theta)_{max}$ in memory and transmit it to an L2 trigger

Take
$\Sigma\Sigma wfm_{\Phi}=\Sigma wfm_{\Phi-1}(\theta)_{max}+\Sigma wfm_{\Phi}(\theta)_{max}+\Sigma wfm_{\Phi+1}(\theta)_{max}$
Trigger on $max(P(\Sigma\Sigma wfm_{\Phi}))$ > threshold

Full Coherent Sum Trigger (1): Computation

Scan every 16 samples (6.2 ns).

For each Φ-sector

For each elevation angle θ=+35,…,-45 $\Delta\theta$=1°

For each azimuthal angle ϕ=+/-22.5 $\Delta\phi$=3°

Delay align the signals in 9 antennas (3 adjacent Φ-sectors) and take the sum $\Sigma wfm_{\Phi}(\theta,\phi)$.

Take the power $P_{\Phi}(\theta,\phi)$ of $\Sigma wfm_{\Phi}(\theta,\phi)$ over 32 samples (12.3 ns).

Find the maximum power $maxP_{\Phi}=max\{P_{\Phi}(\theta,\phi)\}$.

Trigger on $sumP_{\Phi}$ if $sumP_{\Phi}$ > threshold

Cross-correlations (1): Computations

Scan every 16 samples (6.2 ns).

For each Φ-sector

For each elevation angle θ=+35,…,-45 $\Delta\theta$=1°

For each azimuthal angle ϕ=+/-22.5 $\Delta\phi$=3°

Take the correlation

$$X(\theta,\phi) = \sum_{i \neq j}^{32\,samples} \sum_{k} w_i(t_k + \tau_i(\theta,\phi)) \times w_j(t_k + \tau_j(\theta,\phi))$$

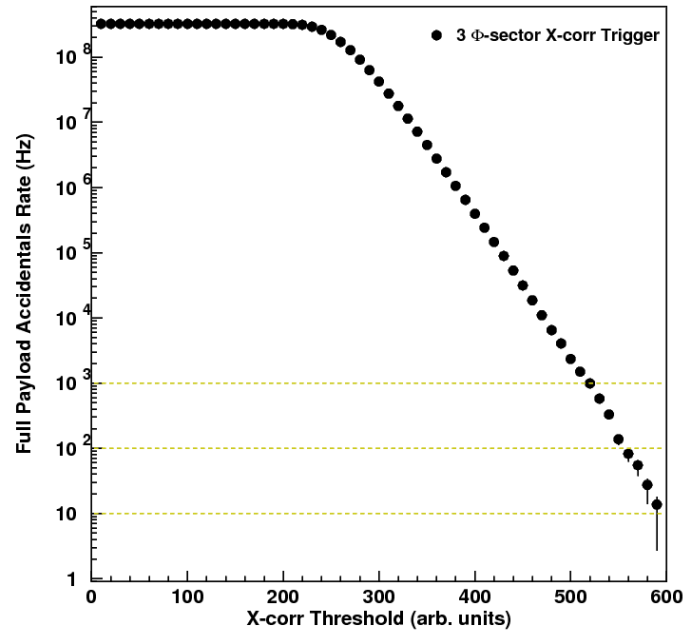
For all waveforms w_i in the set of 3 Φ-sectors.

Find the maximum power $\max X_\Phi = \max\{X_\Phi(\theta,\phi)\}$.

Trigger on $\mathrm{sum}X_\Phi$ if $\mathrm{sum}X_\Phi$ > threshold

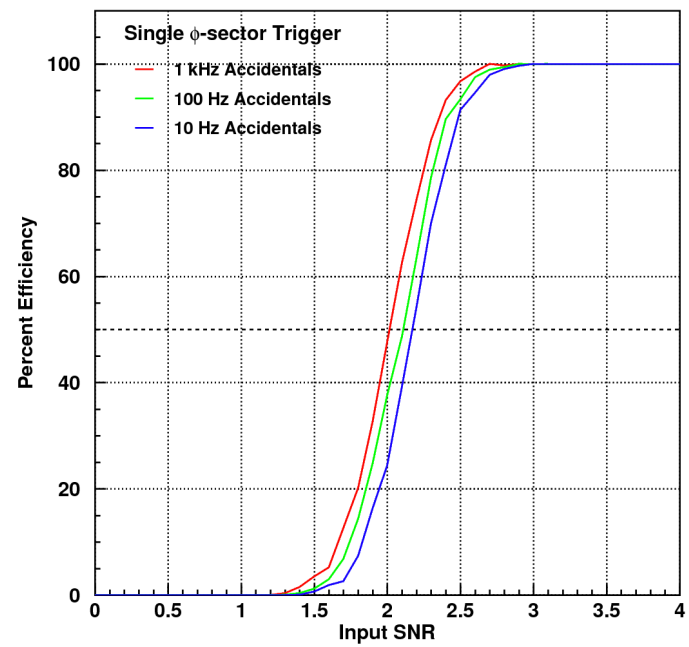
Cross-correlations (2): 3 Φ-Sector Results

Threshold	Rate	50% eff SNR
520	1kHz	2.00
556	100 Hz	2.10
600	10 Hz	2.18



This is worse than coherent waveform sums:

Accidentals Trigger Rate for Full Payload	Coherently Summed Power 50% eff. SNR	Cross-correlation 50% eff. SNR
1 kHz	1.90	2.00
100 Hz	1.96	2.10
10 Hz	2.05	2.18



Estimated Number of Operations per Second

f_s=number of samples per second (sampling rate)

W=window size in number of samples

N_A=number of antennas to be coherently summed

N_θ=number of angles scanned

In a single window for a given direction

$(N_A-1)\times W$ adds: $S[k]=v1[k]+v2[k]+v3[k]$

W multiplies: $S^2[k]$

W adds: $P=S^2[1]+S^2[2]+...+S^2[W]$

$(N_A+1)\times W$ operations

Number of windows per second with interleaving

$2f_s/W$

Nops/s $=2f_s\times N_\theta\times(N_A+1)$

ANITA-3: $f_s=2.6\times10^9$ samples/s $N_\theta=60$ $N_A=3$

Nops/s$\approx1.2\times10^{12}$ ops/s (for each ϕ-sector and polarization)

Estimated Power Consumption

For a CMOS process $\Delta E = C\,V\,\Delta V$ Joules per bit that changes

$\Delta V \approx 1$ Volt

$V \approx 1$ Volt

<u>$C \approx 10$ femtoFarads</u>

$\Delta E \approx 10^{-14}$ Joules / bit

Nops/s~1.2×10^{12} ops/s

Assume that all 3 bits from 3 antennas change for every operation

Power = $(1.2\times10^{12}$ ops/s$) \times (9$ bits/op$) \times (10^{-14}$ Joules /bit)

≈ 0.1 Watts

<u>Total trigger operations power requirement</u>

Total Payload Power=0.1 W × 16 ϕ-sectors x 2 polarizations

≈ 3.2 W

SHORTs alone consume ≈ 50 W