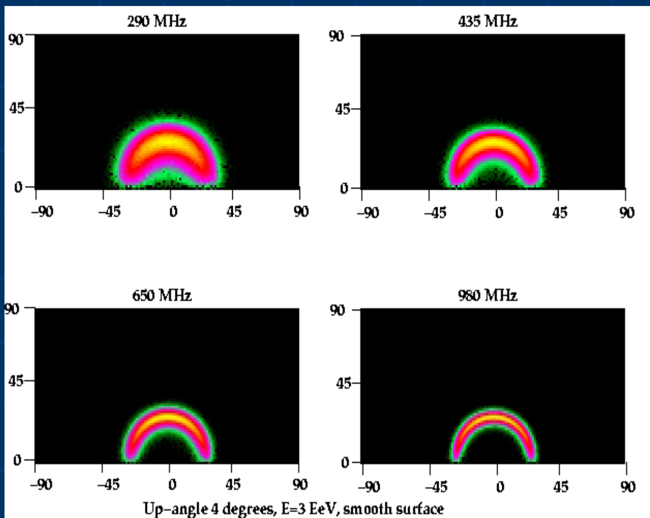
Radio Cherenkov searches for cosmogenic ultra-high energy neutrinos, & ANITA results

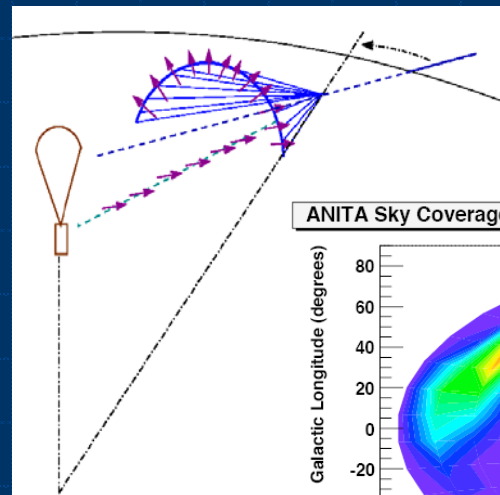
Peter Gorham

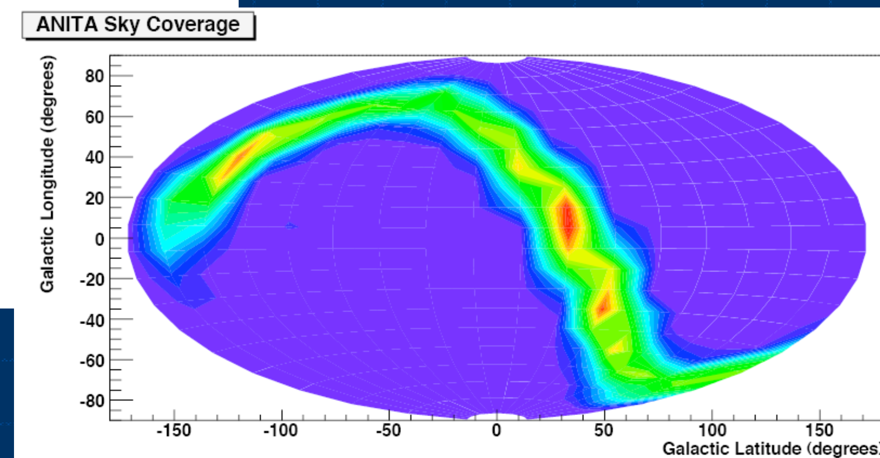
University of Hawaii Manoa

And collaborators at UCLA, National Taiwan University, SLAC, JPL, Univ. Kansas, Washington Univ. St Louis, Ohio State Univ., Univ. of Delaware, Univ. College London

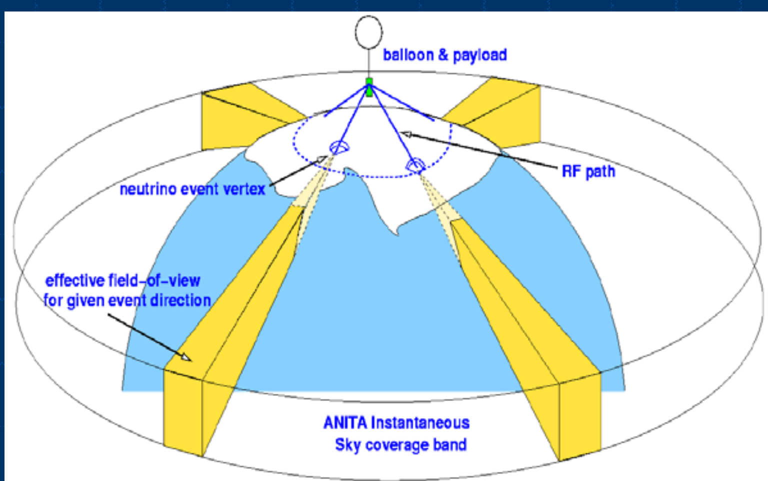
ANITA as a neutrino radio telescope





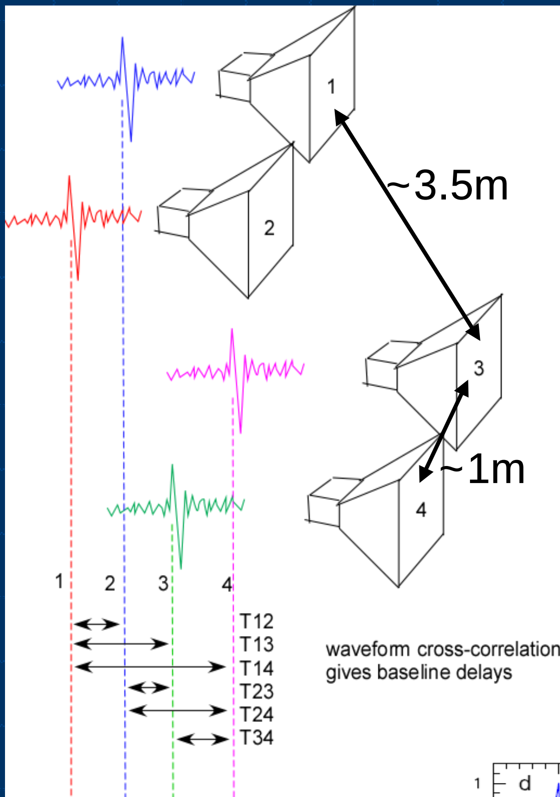


Brian Mercurio & Chris Williams, OSU

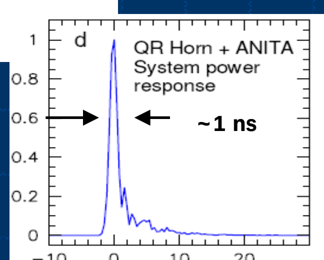


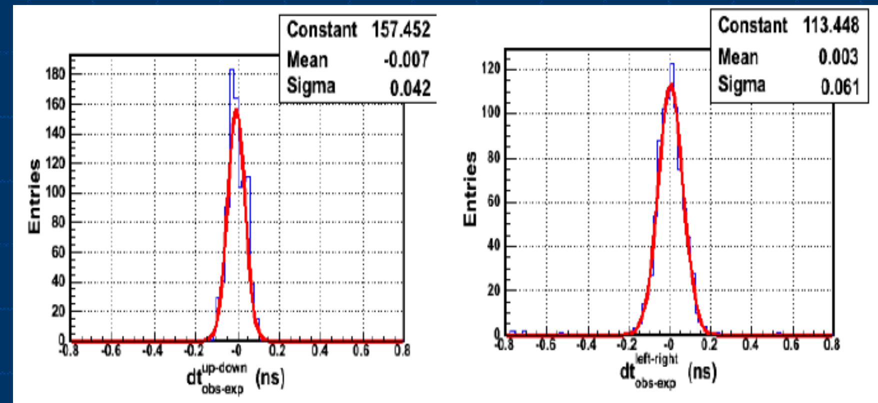
- Pulse-phase interferometer (<30-60 ps timing) gives intrinsic resolution of <0.3^o elevation by ~1^o azimuth for **arrival direction of radio pulse**
- **Neutrino direction** constrained to ~<2^o in elevation by earth absorption, and by ~5-7^o in azimuth by observed **polarization angle of detected impulse**

Pulse phase interferometry



0.2-1.2 GHz bandwidth
➔ 1 ns impulses

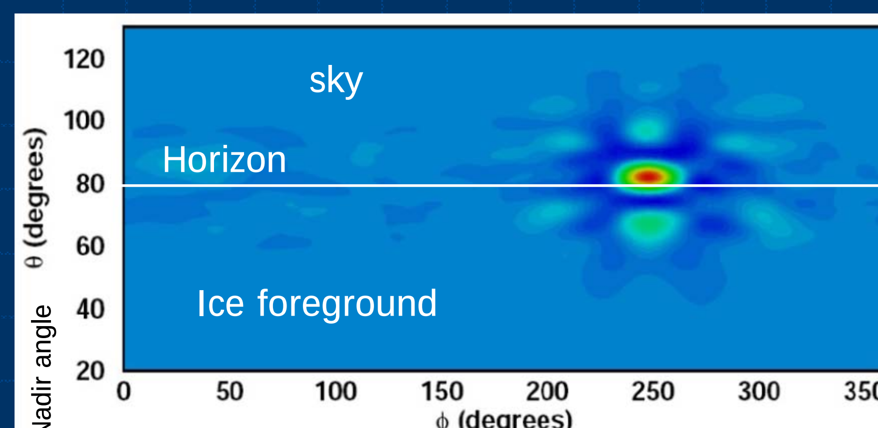




JiWoo Nam, NTU

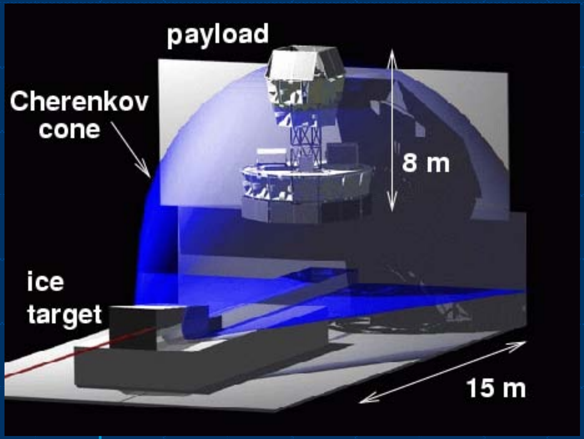
- RF Waveform samplers (G. Varner, UHM)
  - Provide 10 bits, 2.6 Gsamples/sec for 80 channels
- Waveform cross-correlation delay precision determines angular resolution
  - ~30-40 ps (~1 cm) vertical at SNR~5σ
  - ~60-80 ps (2-3cm) horizontal (due to DAQ clock jitter)

End result: map of instantaneous radio intensity,
Method pioneered by UH student Romero-Wolf!



Andrew Romero-Wolf, UHM

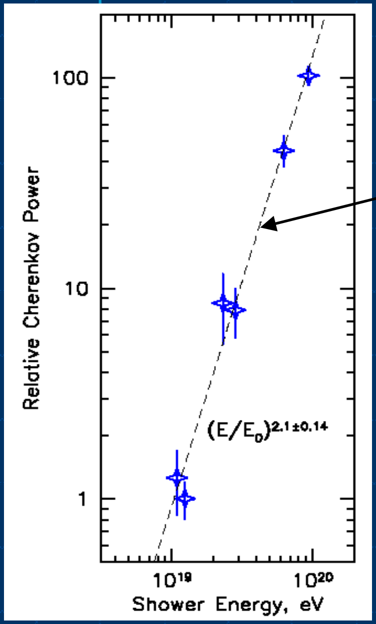
June 2006, SLAC T486: “Little Antarctica”

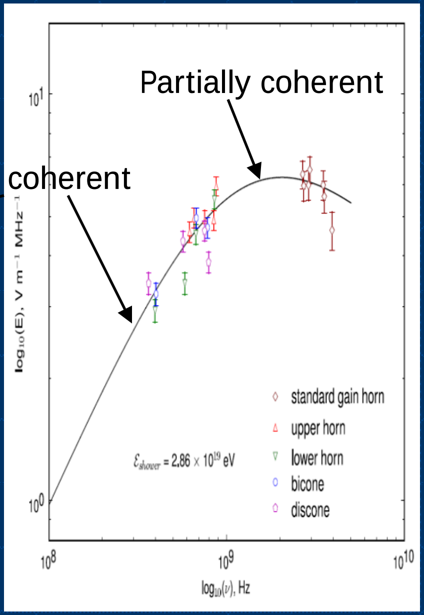


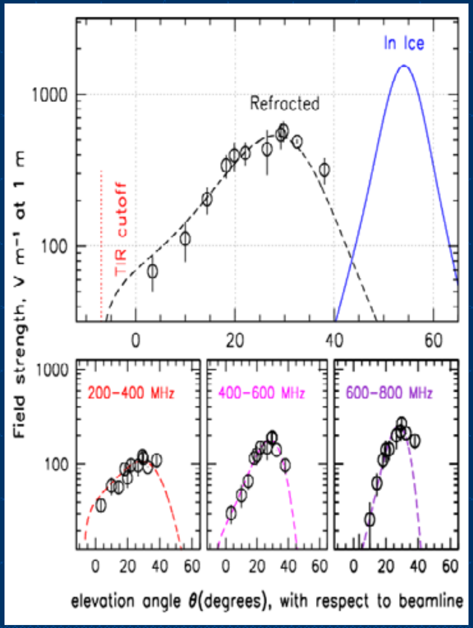
End Station A, SLAC

Thanks to P. Chen, C. Hast, SLAC

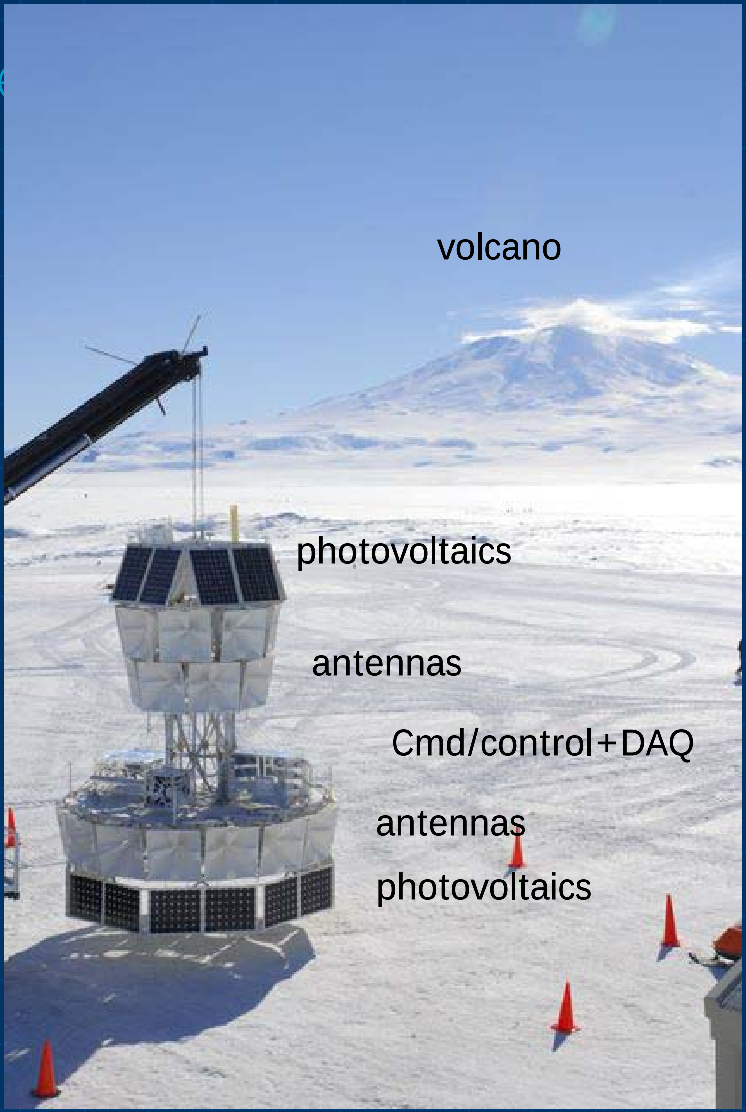
- **SLAC e⁻ showers with composite energy same as UHE neutrinos**
  - **10^{8-9} x 28 GeV $= 2.8 \times 10^{19}$ eV**
- **Coherent radio power, consistent with theory**
- **1st direct observation of radio Cherenkov cone**







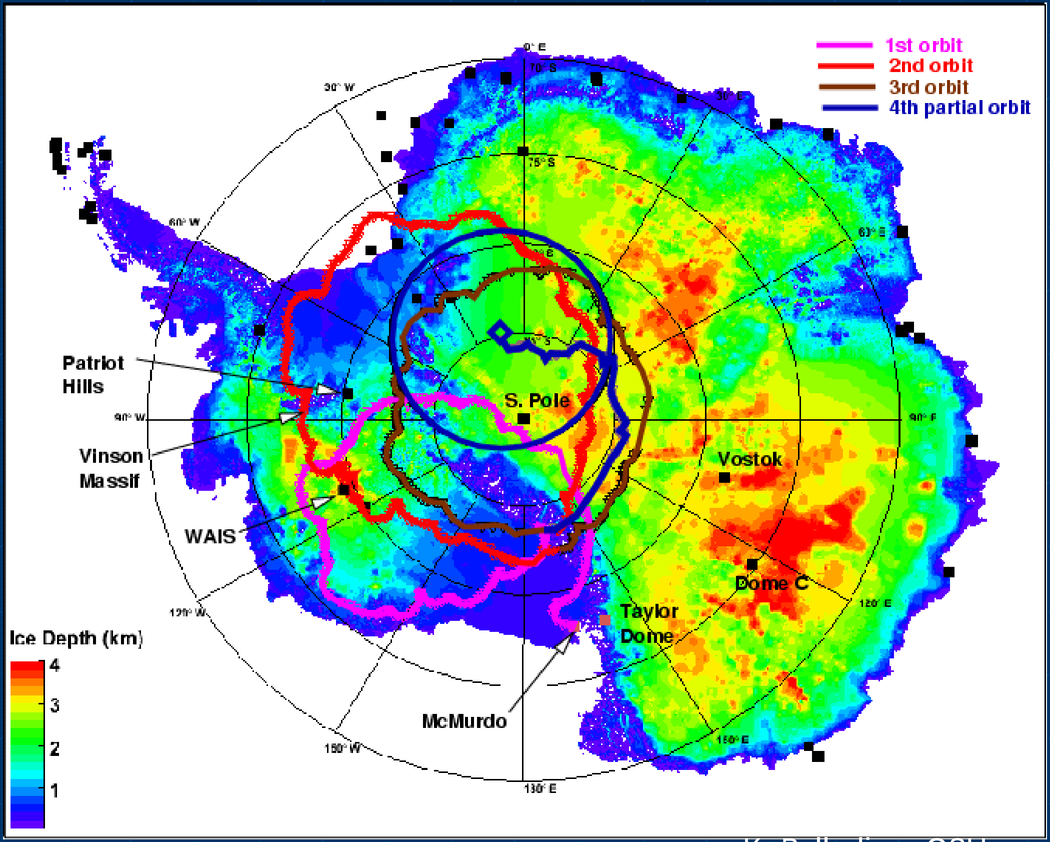
Pre-launch rollout

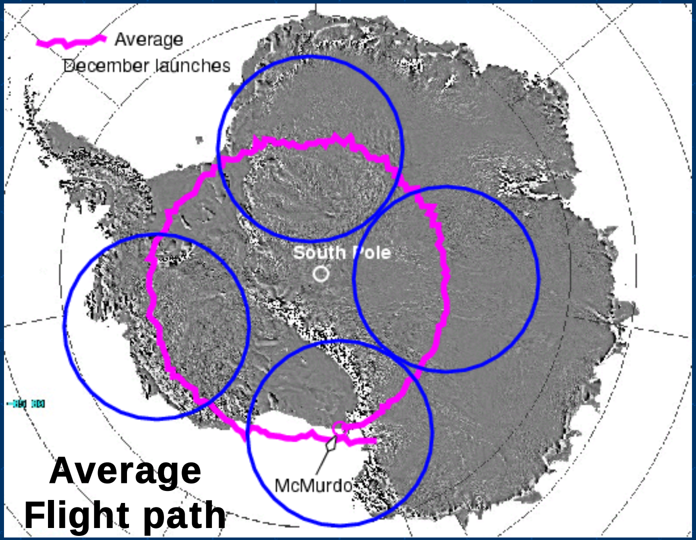


Photos: J. Kowalski

- Launch from ~80m deep Ross ice shelf (floats on Ross sea)
- ~8 miles from McMurdo station
- Affords flat, stable 1-mile diameter launch pad

ANITA-1 flight path

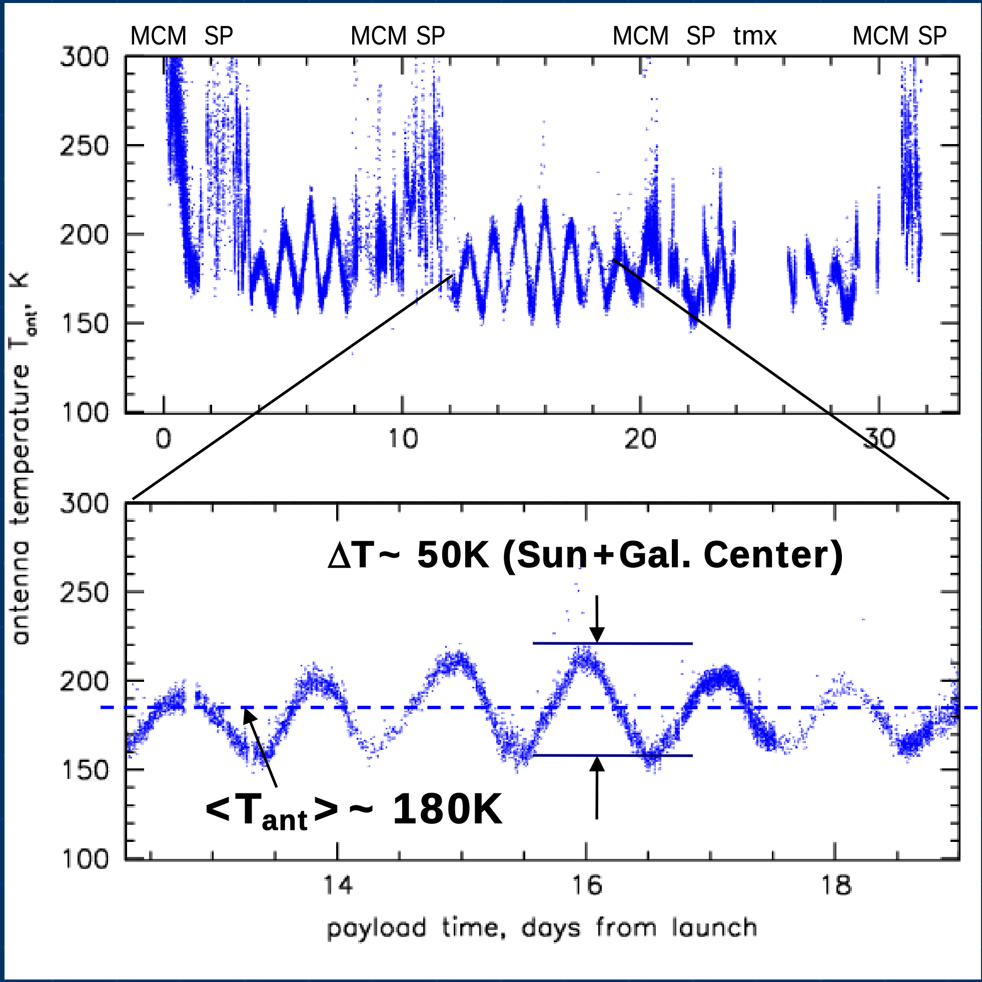




K. Palladino, OSU

- 35 days, 3.5 orbits, but anomalous Polar Vortex conditions
- Stayed much further “west” than average
- In view of radio noise from stations (S. Pole & MCM) ~50% of time
- But still achieved 18 days of good livetime at ~1.2km average depth of ice

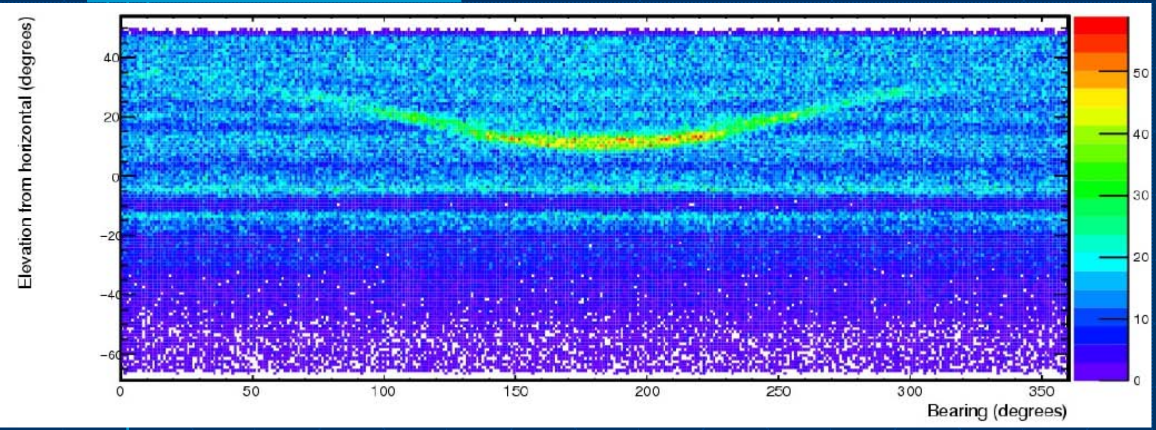
Flight sensitivity snapshot



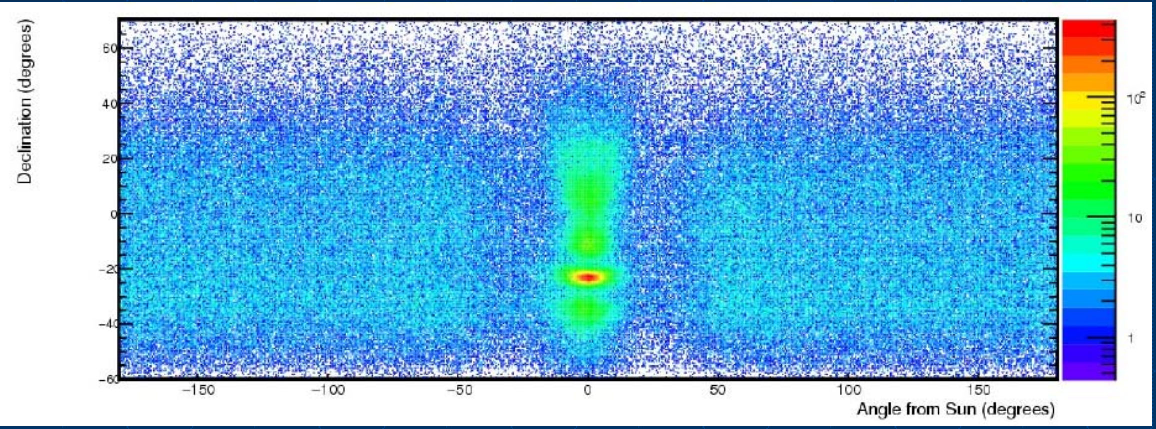
- ANITA sensitivity floor defined by thermal (kT) noise from ice+sky+rcvr
  - T_{rcvr} ~140K
  - T_{ice} ~ 230K
  - T_{sky} ~ 20-80K
- Thermal noise floor seen intermittently throughout of flight—but punctuated by station noise
  - South Pole and McMurdo stations!
- Still a significant fraction (~50-60%) of time with pristine conditions

Solar Sensitivity calibration

Elevation-azimuth coordinates



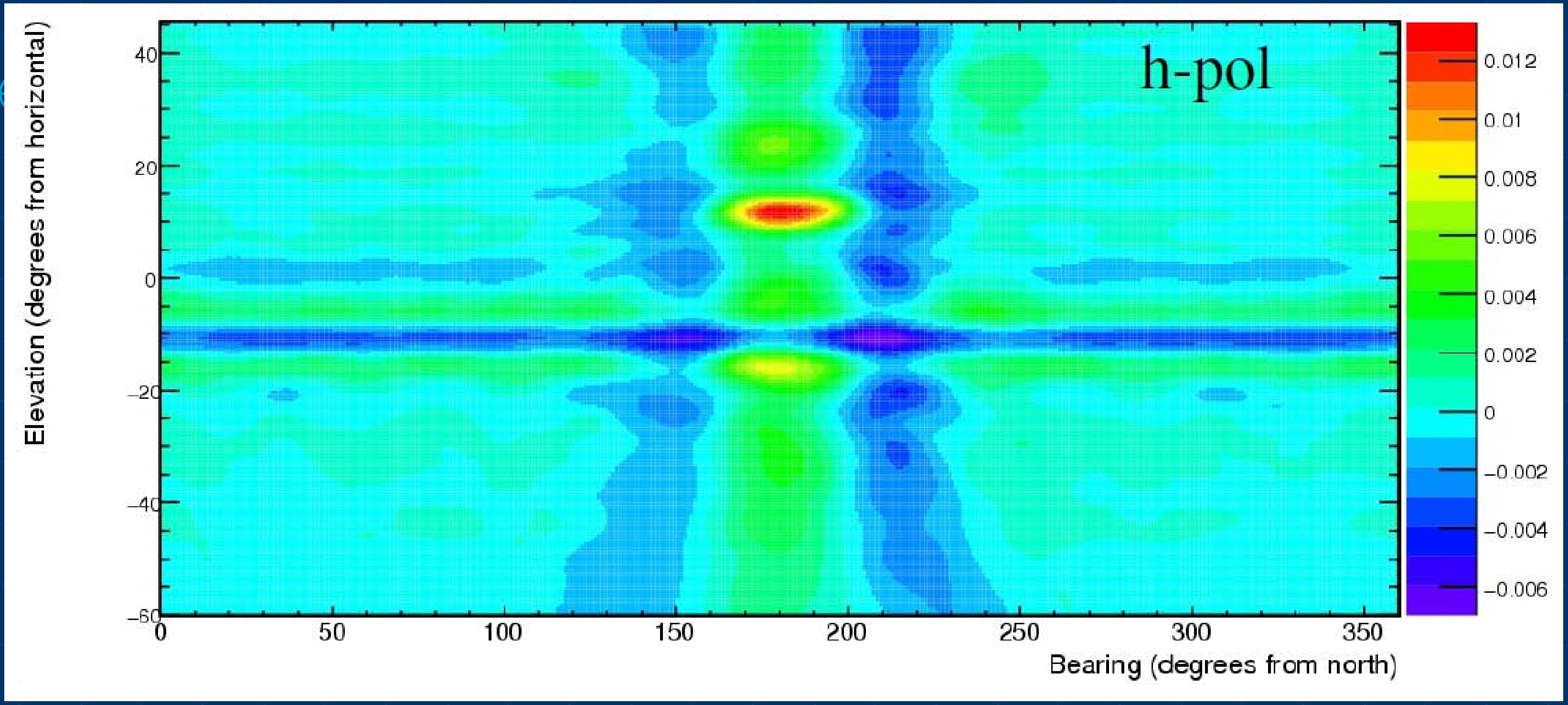
Heliocentric coordinates



Images from S. Hoover, UCLA

- ANITA (~3-5m cluster) interferometric images of the radio sun
  - Flight averages shown here
- Sun detection required about 200 sec of thermal noise data
- Provides 1st-order absolute calibration of antenna noise, beam response, event timing
- Note also horizon (and its sidelobes) at -6 degrees!

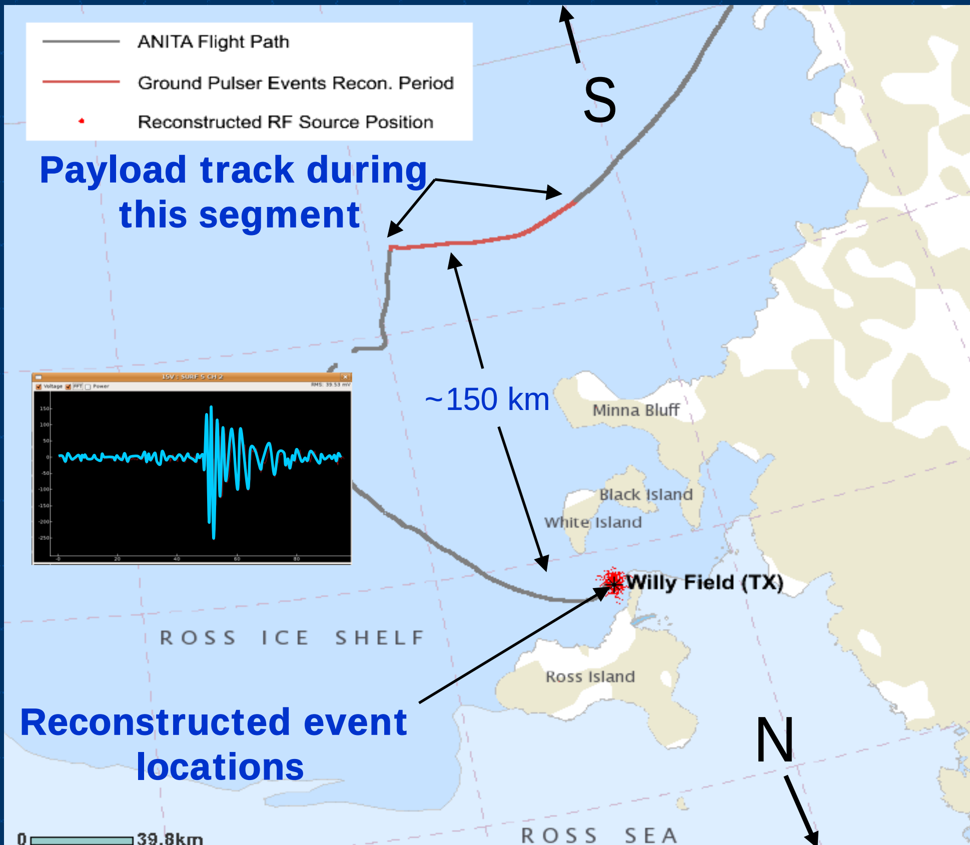
Solar reflection

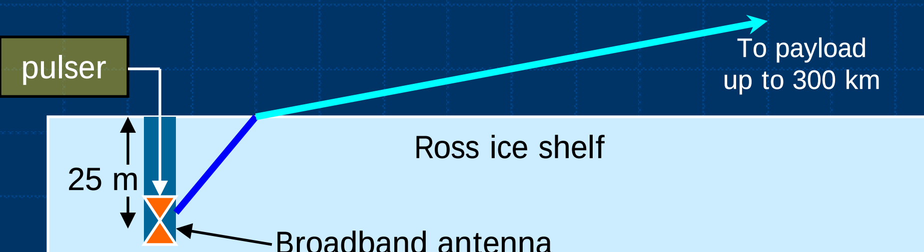


S. Hoover, UCLA

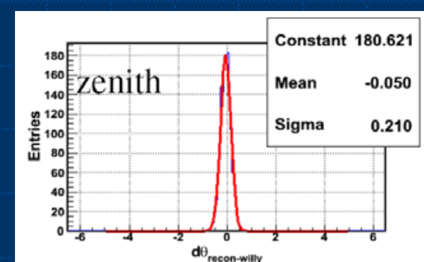
- Higher SNR imaging of the reflected sun in Hpol near Brewster angle
  - Reveals ice surface reflection & Fresnel diffraction pattern of horizon (resolved out by inteferometer)
  - Reflection coefficient confirms relatively smooth ice surface

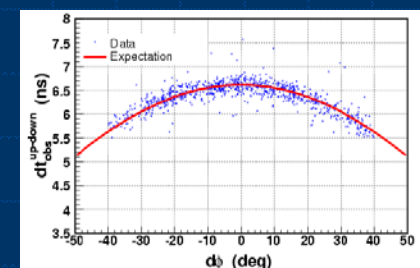
ANITA geo-location of borehole cal events

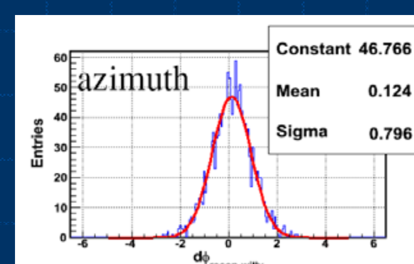


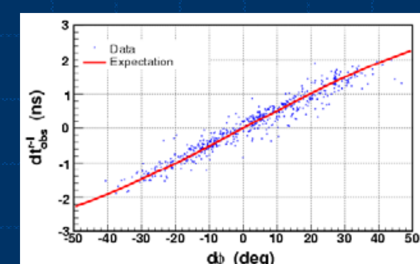


- Expect ~ $c\Delta\tau/2D$ altitude & azimuth
- $\Delta\tau$ ~ 40-60 ps, D ~ 1m (horizontal) to 3 m (vertical)
- Altitude: 0.21º observed, 0.3º expected
- Azimuth: 0.8º observed, 1.7º expected
- Multiple baselines improve constraints
- Pulse-phase interferometry works well!



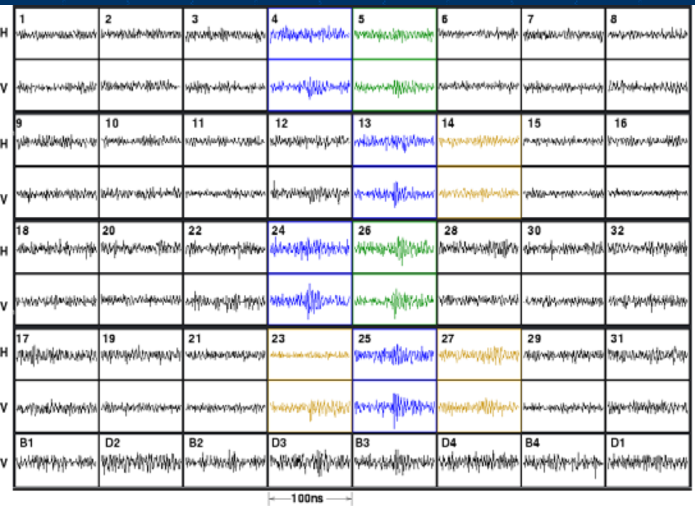


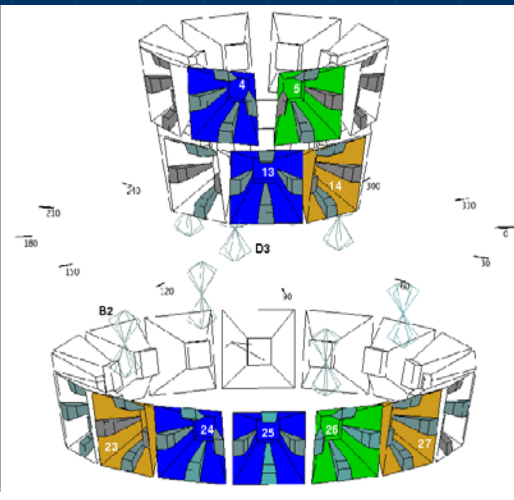


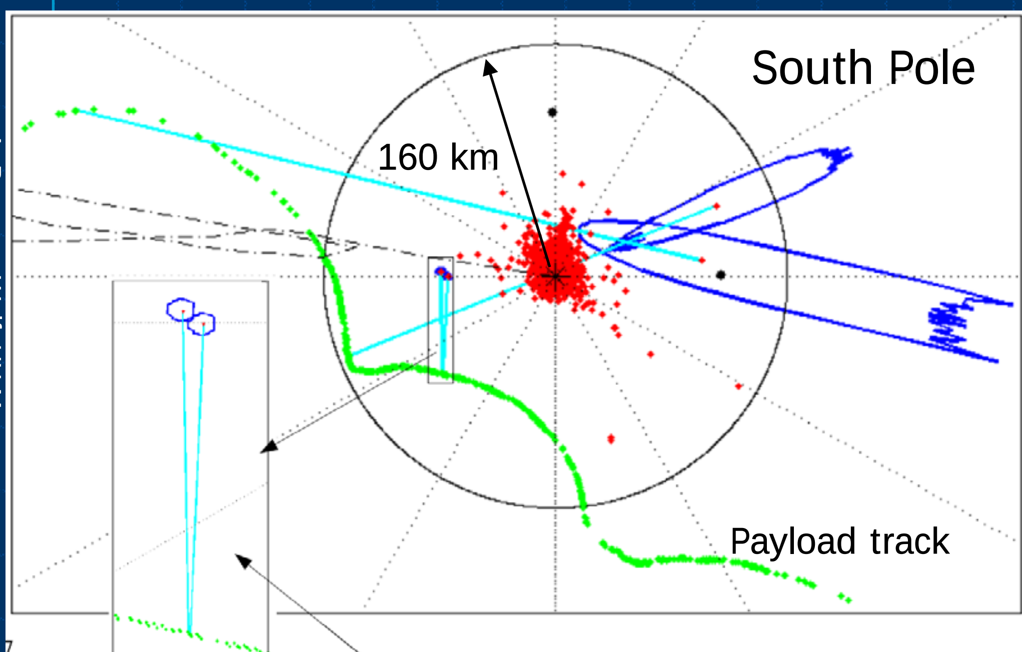


Thanks to JiWoo Nam, NTU

Event reconstruction & analysis



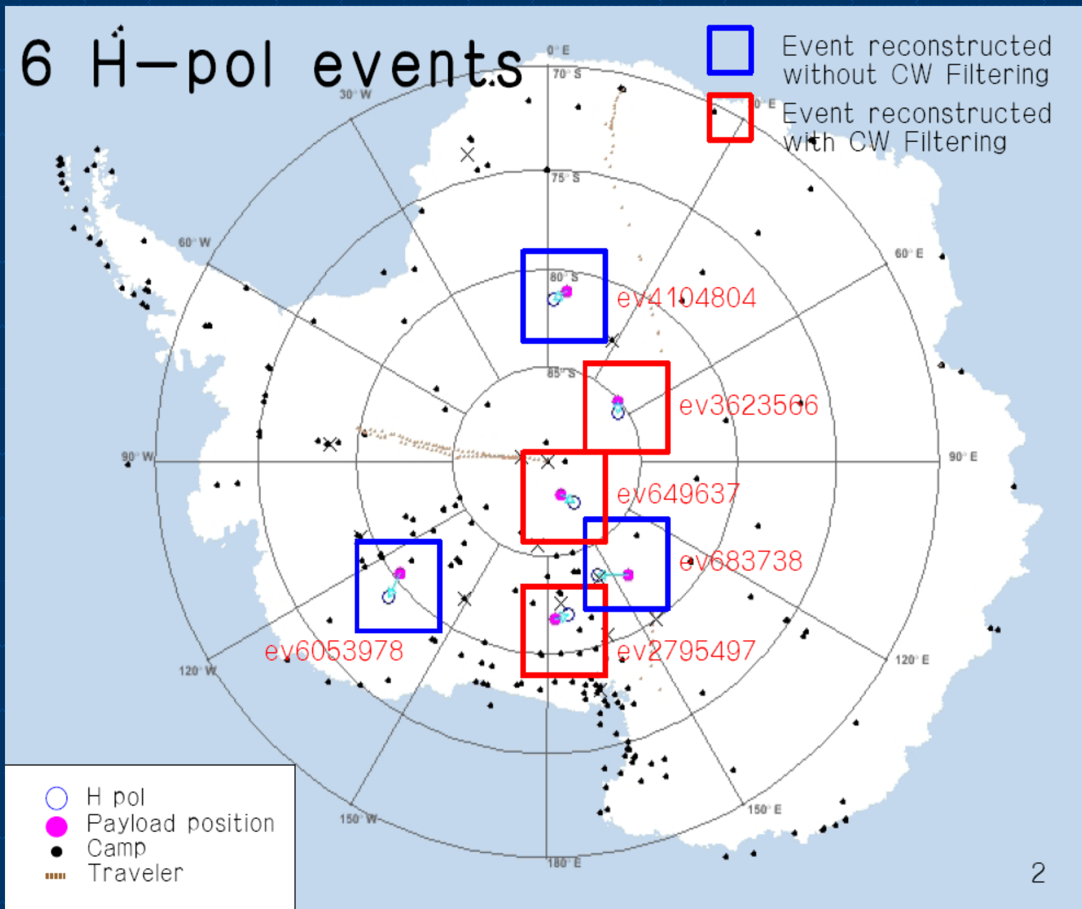




A. Romerro-Wolf, UH Manoa

- Raw data: RF plane-wave lights up one side of payload
- Waveform corrletor (offline) gives 30-60ps timing
- Reconstruct ground position & error ellipse
- If <3σ from camp or any other event, reject
- South pole EMI, calibrated borehole pulser at MCM used to calibrate timing & statistical behavior

Initial unblinded higher-threshold event set

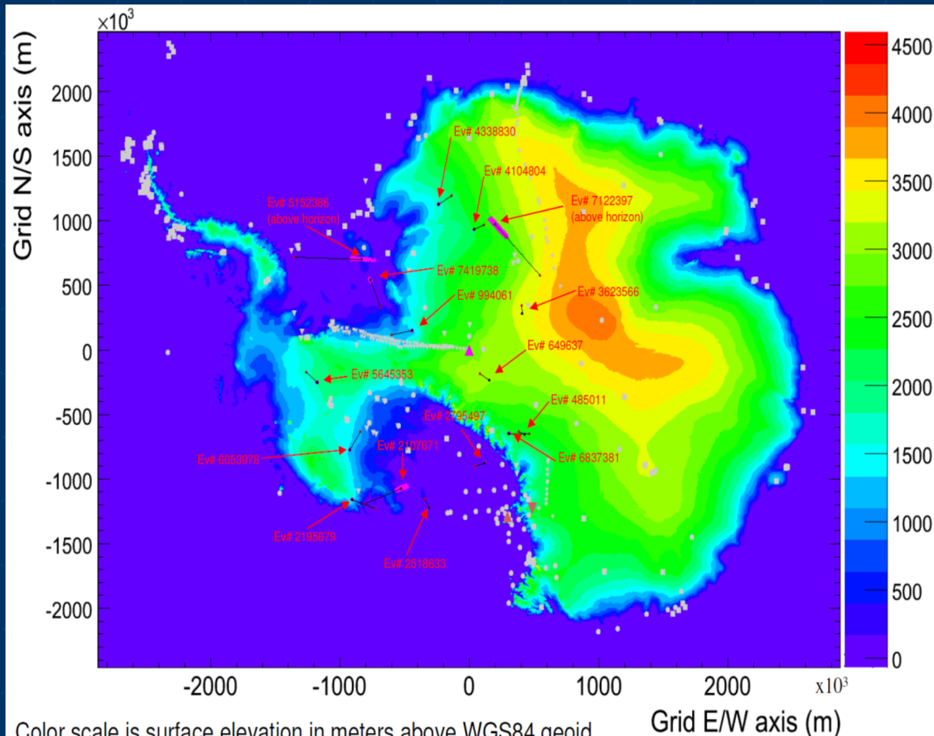


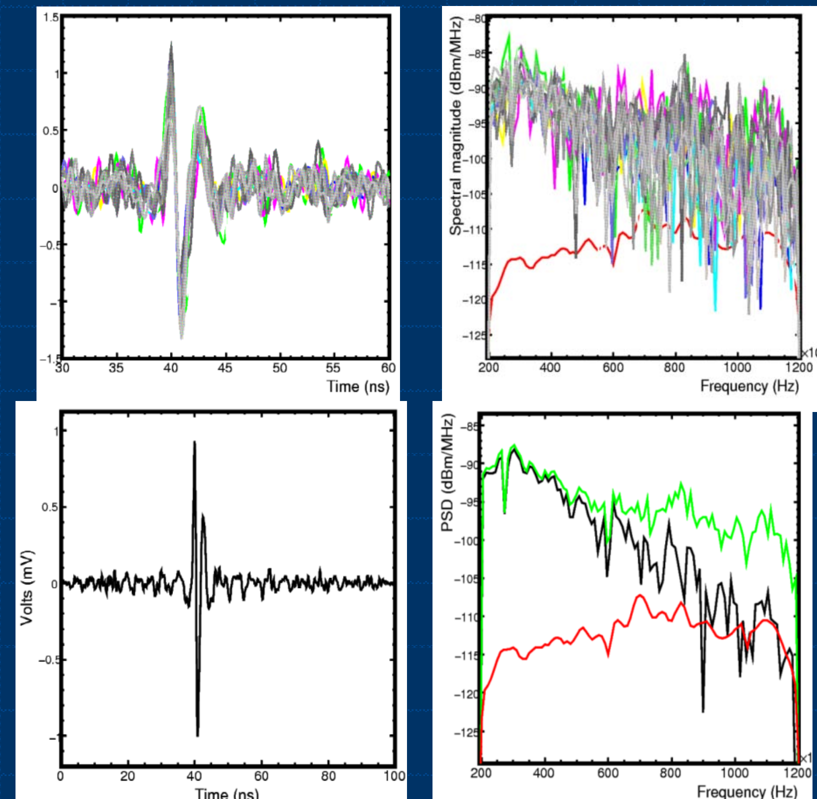
Jiwoo Nam, NTU

- ~19K events (9.6K Vpol & 10K Hpol) are impulsive & reconstruct to Antarctic ice locations
- Exclude all repeating locations (H,V,H+V)
- Exclude single events within ~50km from known sites
- After cluster+camp rejection:
  - 0 V-polarized (no askaryan-like signals➔ no neutrinos)
  - 6 H-polarized events left

“camp” = any man-made installation, active or not
- most are inactive, many may be gone in fact
- but exposed metals could discharge

ANITA-1 lower threshold analysis

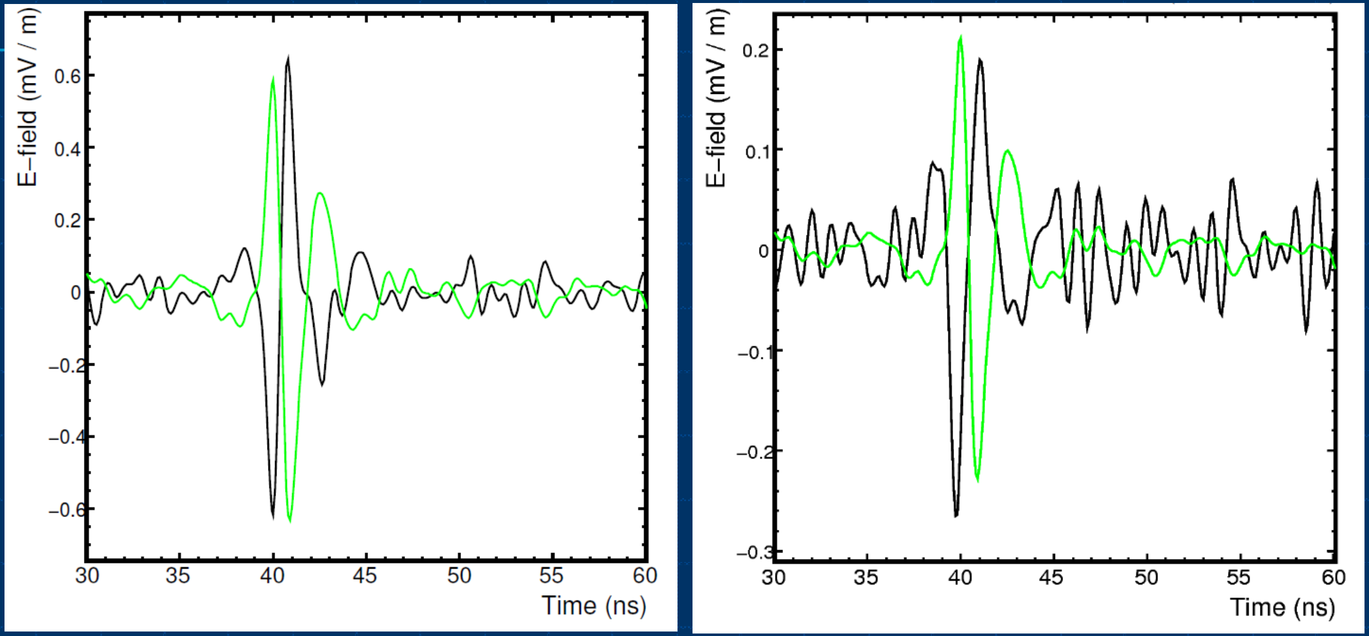




Stephen Hoover UCLA

- Independent deeper analysis done at UCLA
- Detected: **no neutrino candidates**, all of original 6 Hpol events, **+10 more**
- Hpol events: good coherence, not like any anthropogenic signals, low-frequency-dominated

2 of 16 Hpol events were unusual...

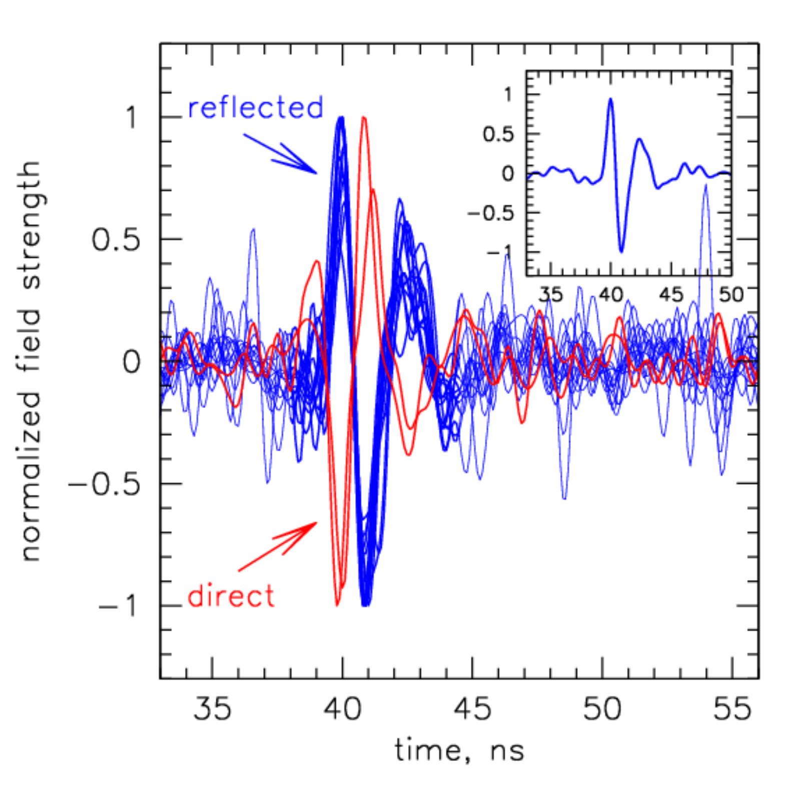


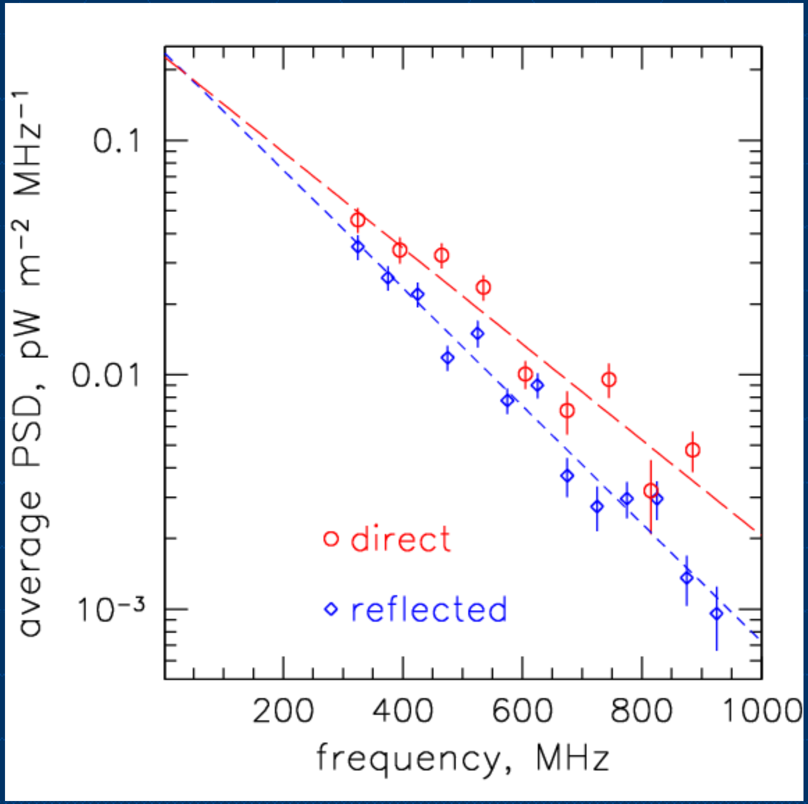
Images from S. Hoover, UCLA

- Both of these impulses were seen from directions above the horizon, but below the horizontal
- Green: average of 14 events with same-sign
- Black: above-horizon events: phase is 180 degree inverted!
  - Reflections cause phase inversion → are these the direct signals of the same process as the 14 others?

Radio pulse waveform & spectrum

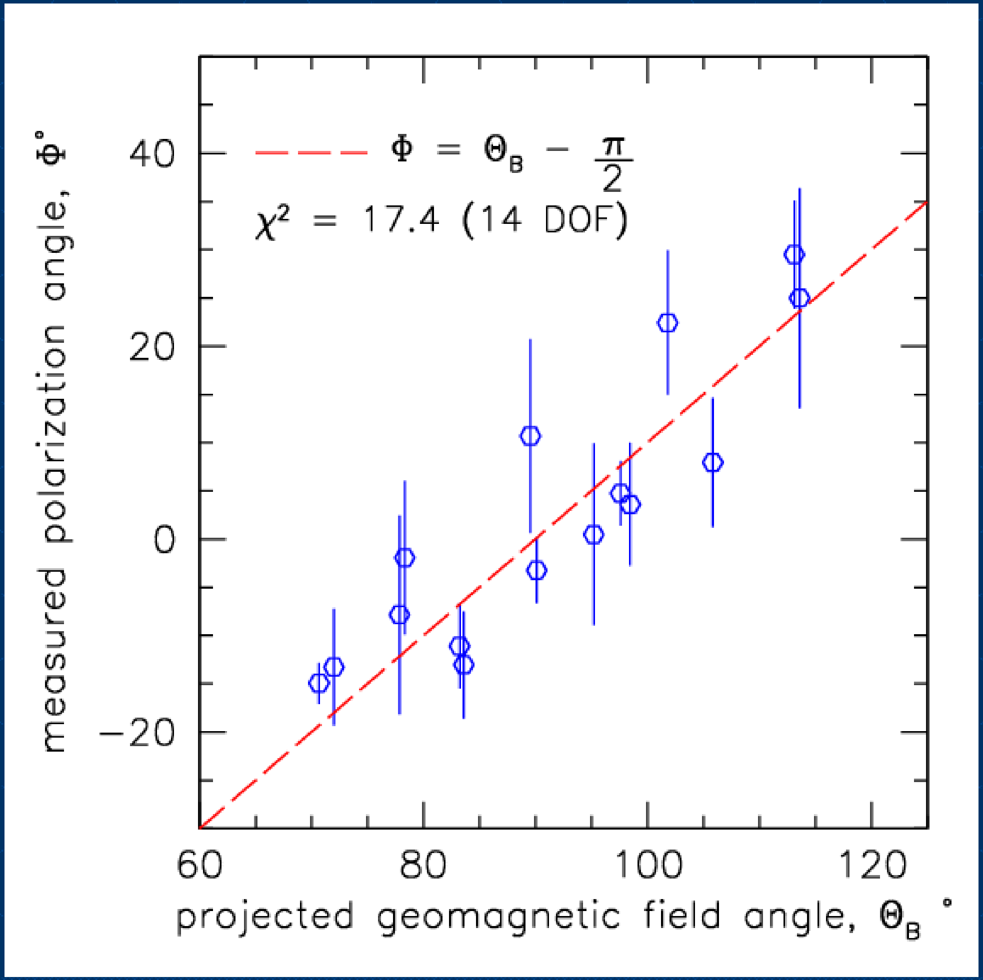
Data from S. Hoover, UCLA





- Normalized waveforms – all very similar (180 deg phase-flipped for 14 reflected waveforms – here knowledge of phase – via careful group-delay calibration -- was **critical!**)
- Spectrum (first ever broadband in this range) best fits exponential, power law not ruled out. **Amplitude calibration** critical here (not perfect, 200-300 MHz band still suspect)

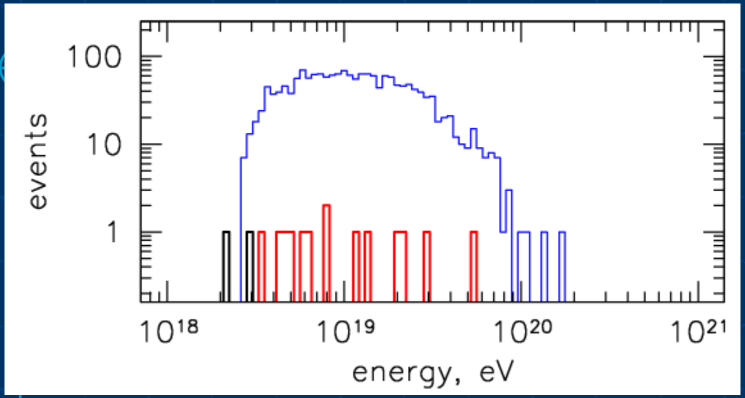
Correlation to local B field



Stephen Hoover UCLA

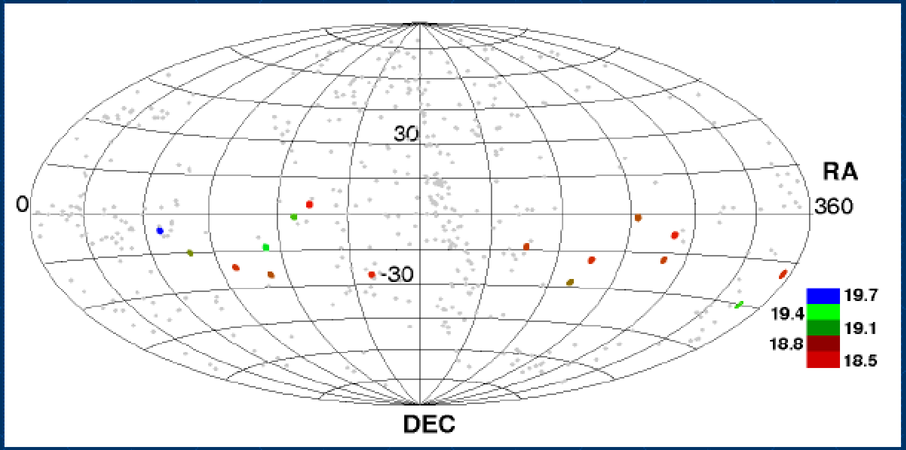
- All of UHECR candidates showed radio polarization perpendicular to local B-field direction (mostly vertical)
- Very difficult to do without some relation to Lorentz force F= qv x B!
- Background signals: random correlations always!

Energy scale, directions



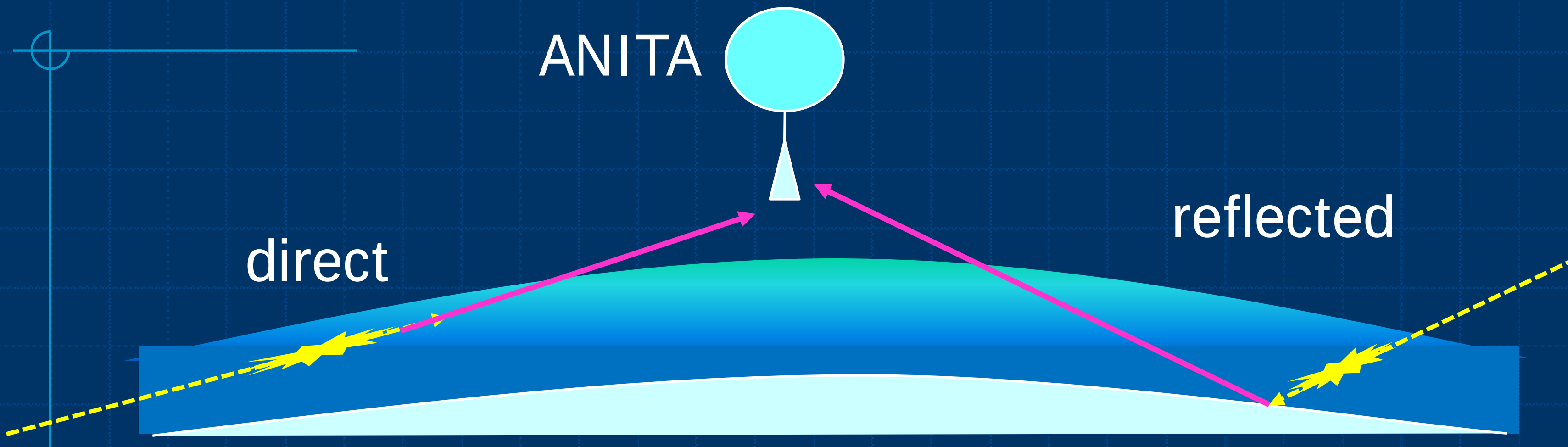
Red: events, blue: Monte Carlo, black: above horizon

$$\langle E \rangle = 1.5^{+2}_{-0.4} \times 10^{19}\ \mathrm{eV}$$



- If we try to use REAS2/3 results (Tim Huege et al)
  - Energy scale is very high, <E> ~ 4e19 eV
  - But model parameters don't fit the data well
- Alternative approach: data-driven Bayesian max likelihood fitter
  - Allow radio intensity & angular parameters to float within model priors
  - Results: energy scale is lowered, but with large asymmetric errors

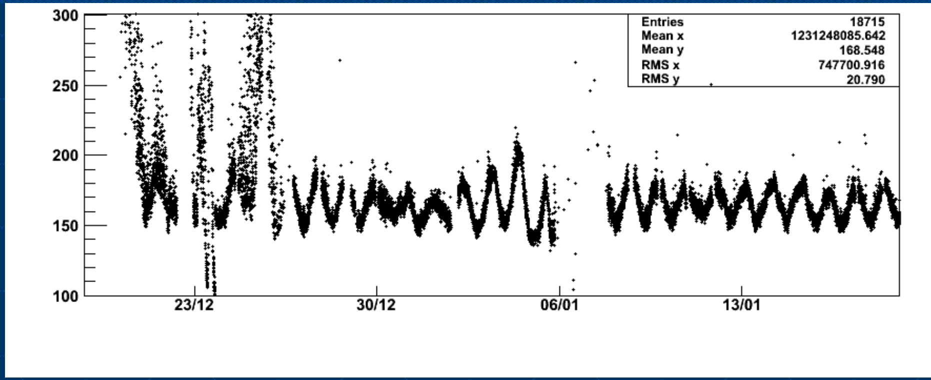
ANITA as a UHECR telescope?

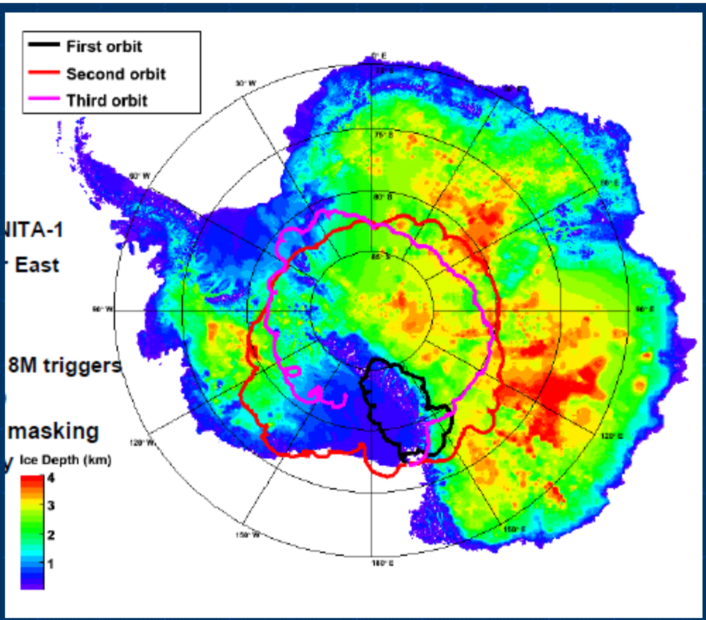


- If hypothesis of UHECR radio signals is correct, direct events have much less acceptance than reflected
  - Reflected events can come from a wide range of angles
  - Direct events have only a narrow stripe near the horizon
- UHECR energy spectrum well-measured, so test this with a simulation

ANITA-2 launch Dec. 2008

ANITA-II

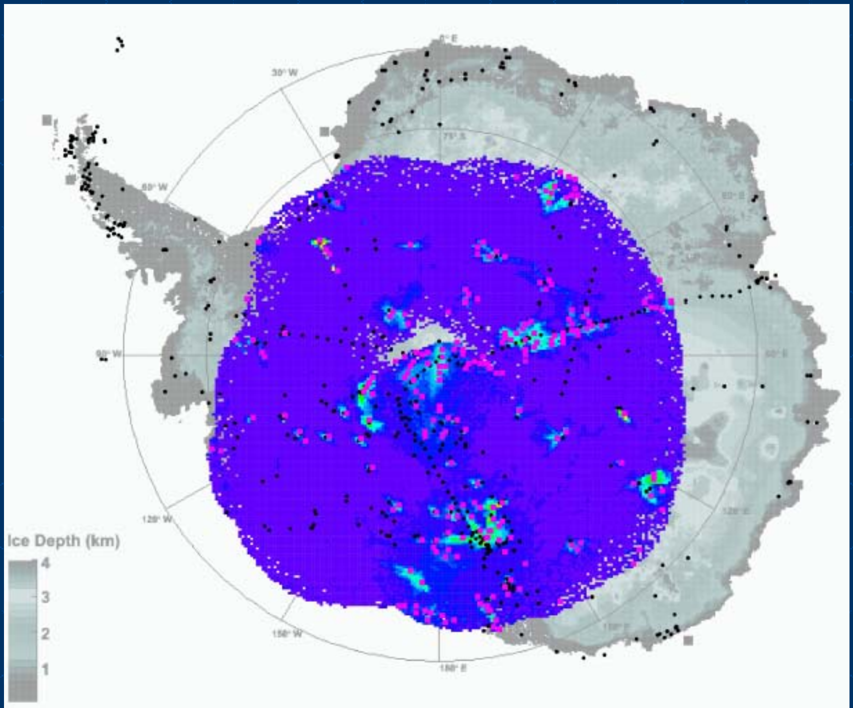


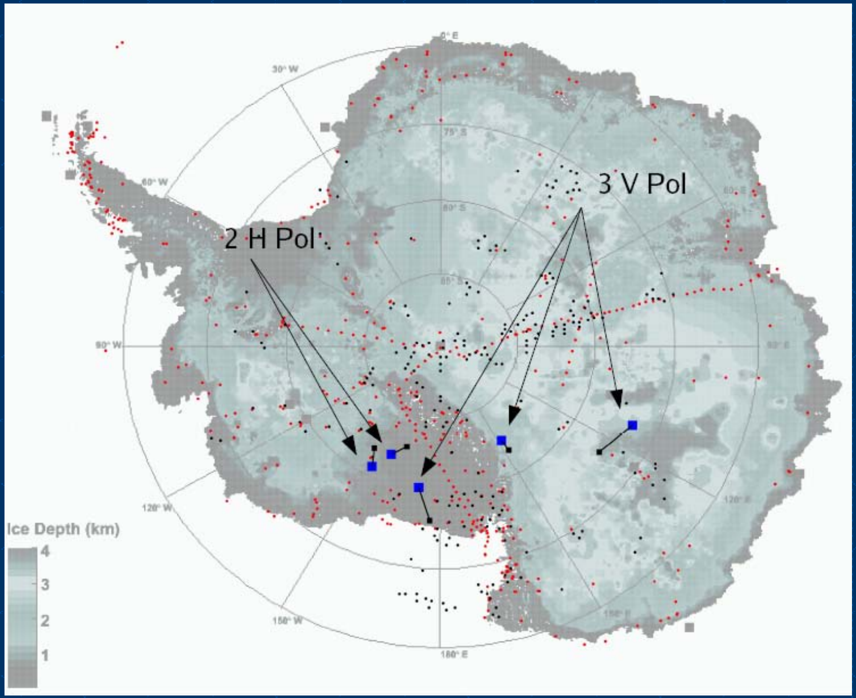


- ANITA-II: 31 days at float, >70% in radio-quiet conditions
- Collected 3x as much data as ANITA-1
- Angular resolution ~50% better
  - Less ice “lost” to camp peripheries

- Predicted sensitivity increase verified by in-flight calibration (pulsers + cosmic srcs)

ANITA-II analysis

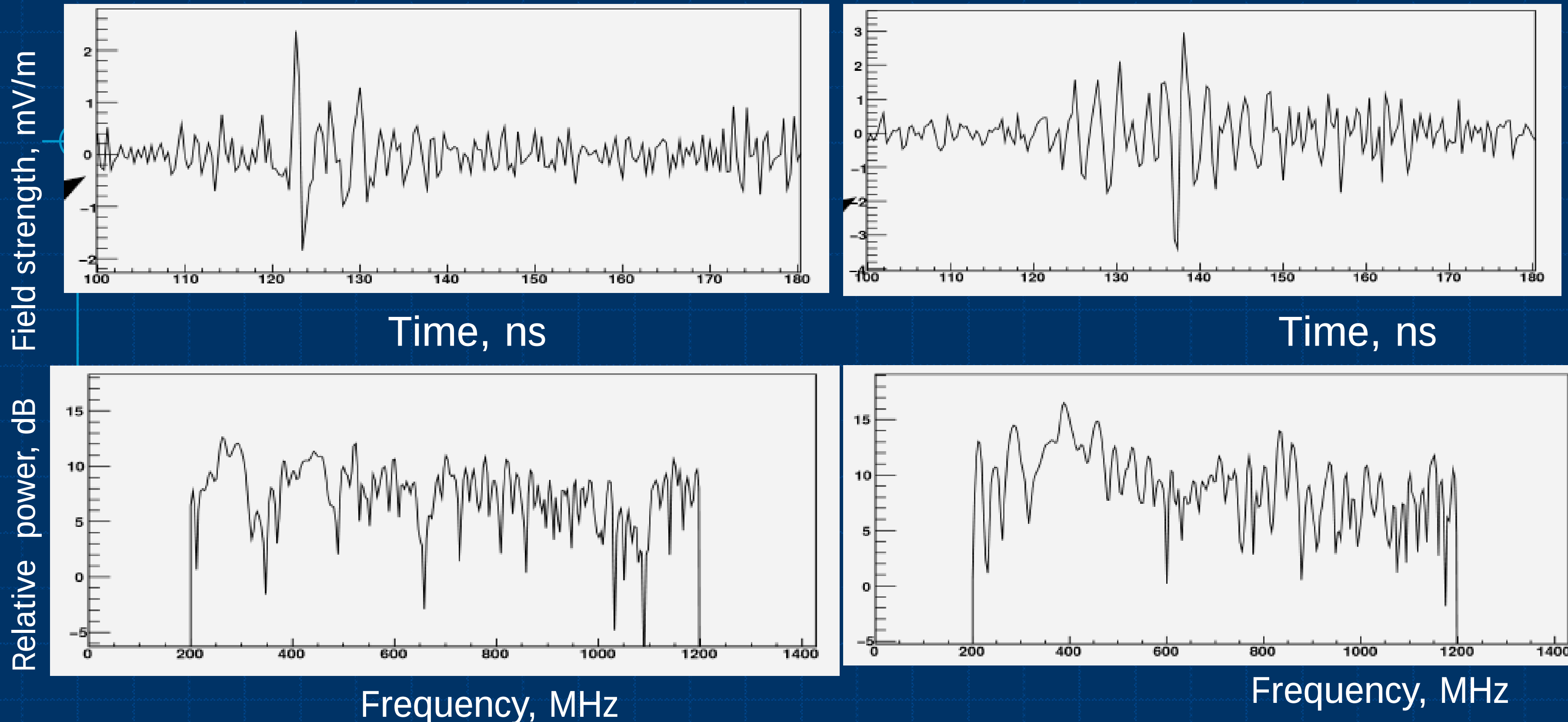




Images from Abby Vieregg, UCLA

- Left: map of background RF intensity for ANITA-II, with “quiet” ice (pure thermal) in violet, ‘hotspots’ in light blue, camps,traverses, flight paths ==black dots
  - Everything not consistent with thermal gets effectively excluded from search region
  - (Methodology of map on left another A. Romero-Wolf invention!)
- Right: final sample after unblinding: 2 Hpol, 3 Vpol (but where are the UHECRs??)
  - **Trigger tuned for max neutrino sensitivity at the expense of cosmic rays – before we knew we were a UHECR telescope! (will do better next flight)**

Survivors

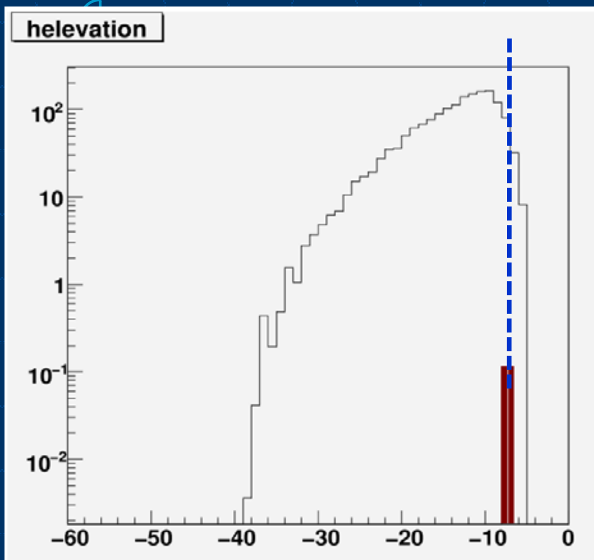


Images from Abby Vieregg, UCLA

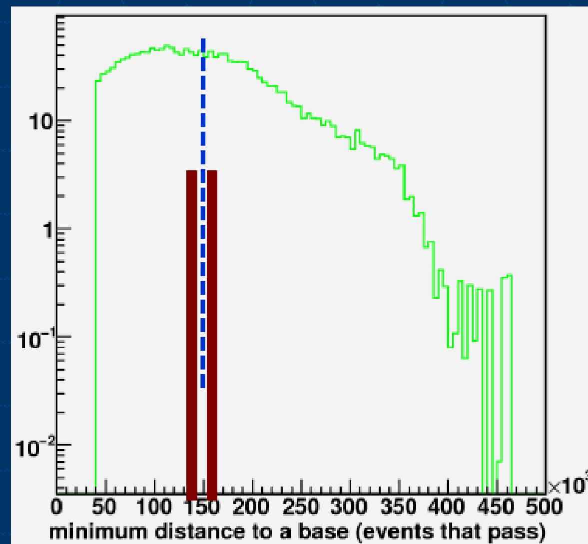
- 1 of 3 Vpol survivors had sub-threshold partners
  - Anything that repeats cannot be a neutrino!
- Two remaining events: highly Vpol (>80%), flat spectrum, not near any camps, consistent neutrino simulations

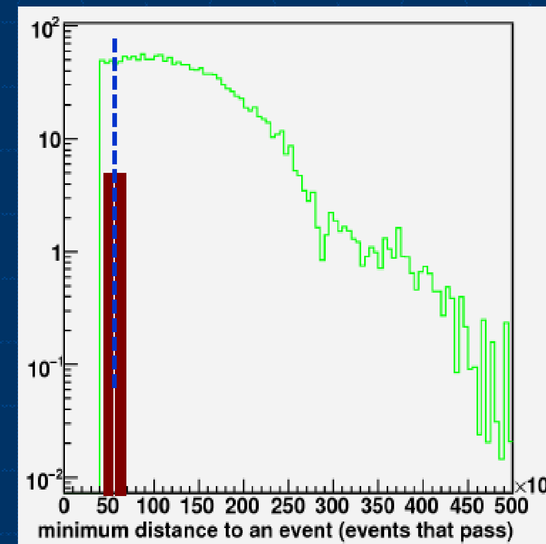
Consistent with neutrinos?

black: neutrinos
Red: events



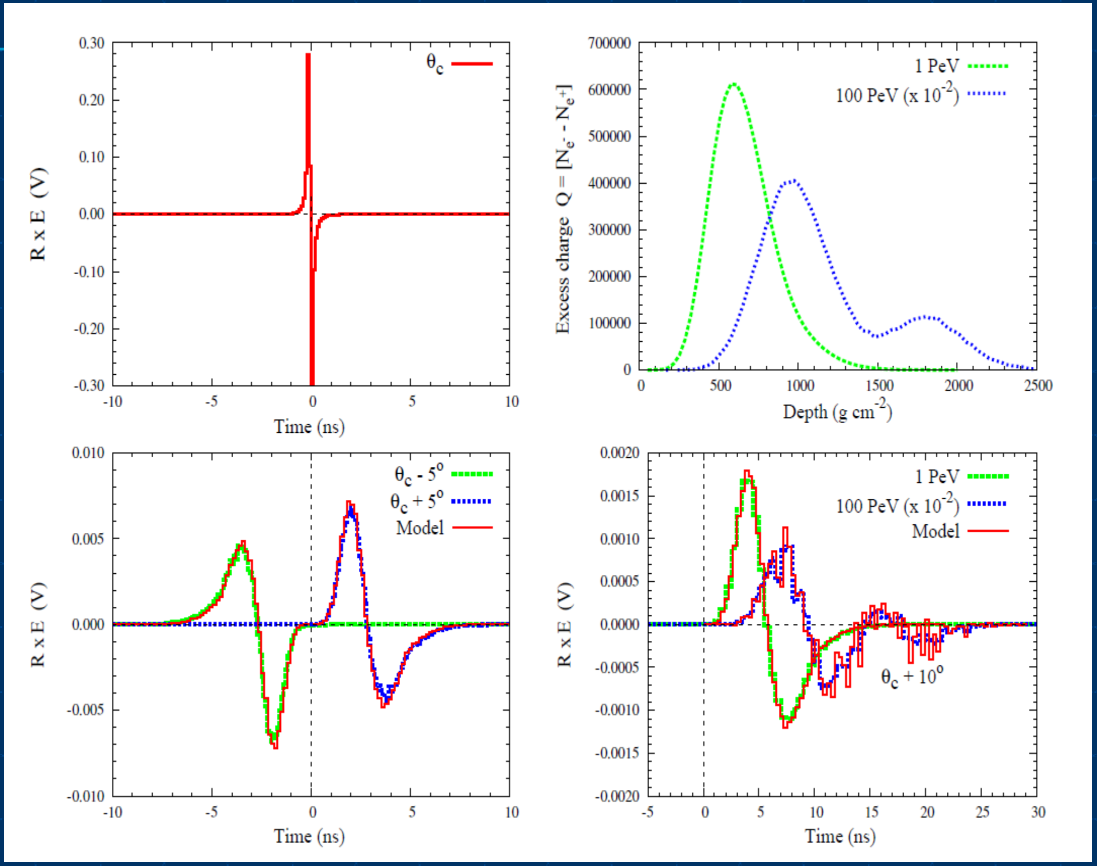
Green: neutrinos
Red: events





- These distributions were *not* used to make any cuts on blind event sample
- More distributions to come, but so far events appear to have similar distributions as simulated neutrinos
- for rightmost plot, green should not have been cut off, but events still seem relatively close to other events (but passed the clustering cut)

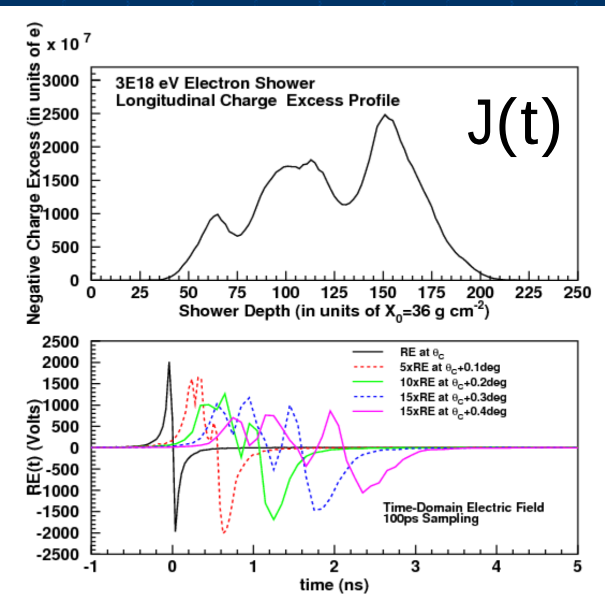
Shower to waveform mapping

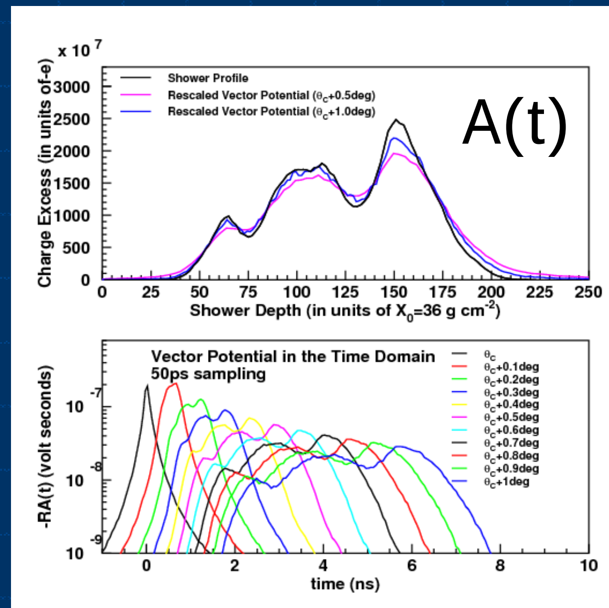


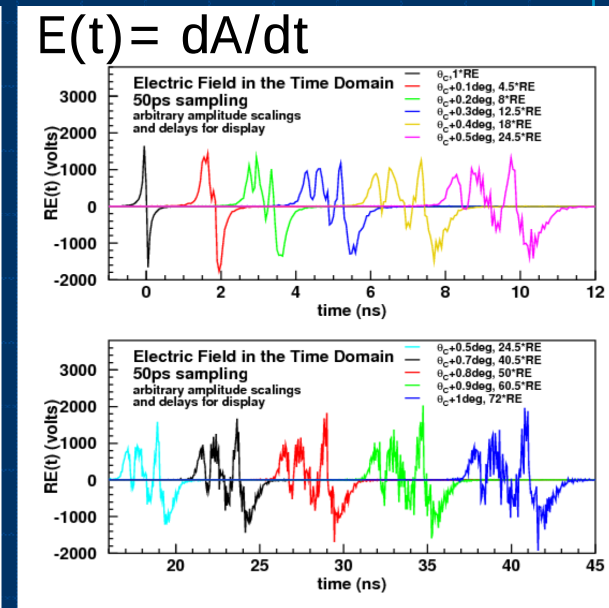
Alvarez-Muniz, Romero-wolf, Zas, arXiv 1002.3873 2010

- Time domain waveform off the Cherenkov angle:
  - Vector potential *A* maps shower current to far-field
  - Electric field: determined from time derivative of A
- Waveforms (phase & amplitude) encode interaction!

Shower to waveforms (2)







- A. Romero-Wolf (UH), working with Alvarez-Muniz & Zas
  - New formalism for inverting waveforms to determine shower properties
  - Waveform shape at the sub-ns level encodes the intrinsic shower profile
  - LPM showers can produce very “ratty” pulse shapes – but these are the highest percentage of showers that trigger near threshold
  - Underlines potential importance of good waveform sampling

ANITA-II results summary

TABLE I: Event totals vs. analysis cuts and estimated signal efficiencies for the ANITA-II data set

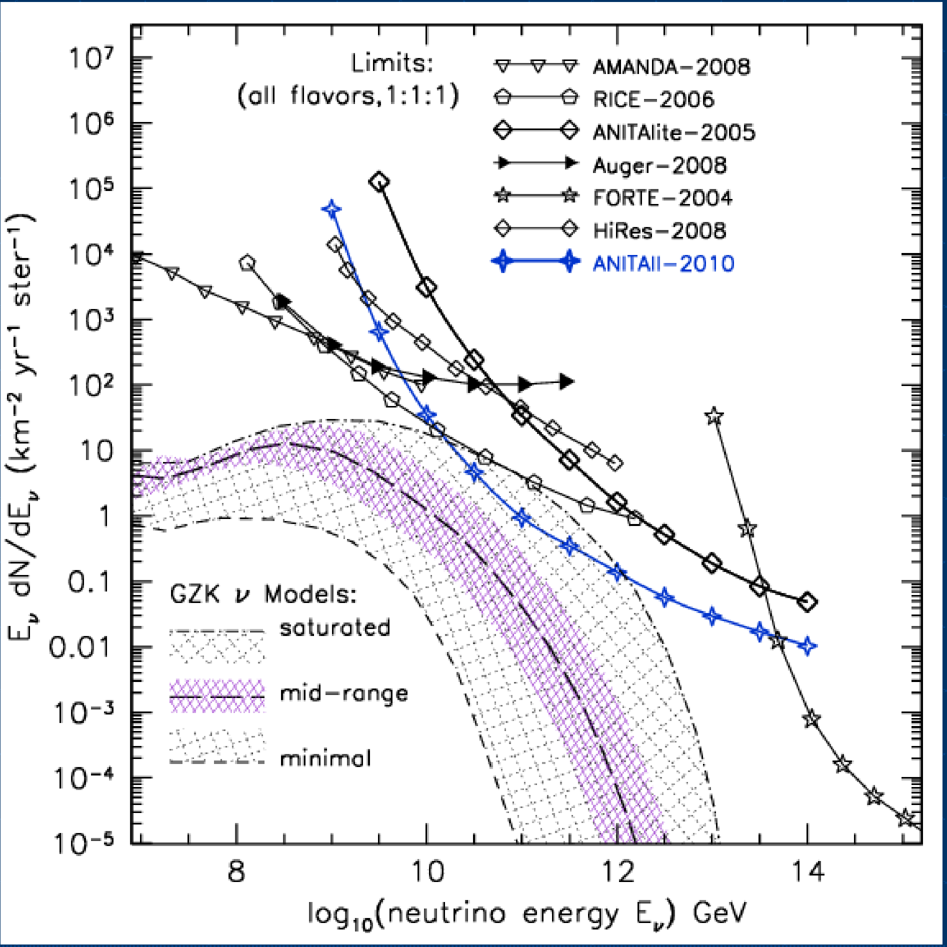
Cut requirement passed:	Vpol	Hpol	Efficiency (ESS)
(0) Hardware-Trigger	$\sim$ 26.7M	$\sim$ 26.7M	
(1) Quality Event	$\sim$ 21.2M	$\sim$ 21.2M	1.00
(2) Reconstructed Event	271,824	48,898	0.93
(3) Event-isolated	15	7	0.718
(4) Not Payload Noise	12	7	1.00
(5) Not Misreconstruction	9 or 10	4	1.00
(6) Hot Spot-isolated	4 or 5	3	0.957
(7) Camp-isolated	2 or 3	3	0.930
Total Efficiency			0.592

TABLE II: Expected numbers of events N_ν from several UHE Cosmogenic neutrino models, and confidence level for exclusion by ANITA-II observations.

Model & references	predicted N_ν	**CL,%**
Baseline models		
Protheroe & Johnson 1996 [22]	0.49	19
Engel, Seckel, Stanev 2001 [11]	0.28	14
Stanev 2006 [?]	0.29	14
Barger, Huber, & Marfatia 2006 [30]	0.89	29
Berezinsky 2005 [?]	0.61	22
Strong source evolution models		
Engel, Seckel, Stanev 2001 [11]	0.87	29
Aramo *et al.* 2005 [27]	2.2	62
Berezinsky 2005 [?]	4.67	92
Barger, Huber, & Marfatia 2006 [30]	2.8	73
Yuksel & Kistler 2007 [29]	1.44	44
Models that saturate all bounds:		
Yoshida *et al.* 1997 [?]	25	$>$ 99.999
Aramo *et al.* 2005 [27]	15.6	99.999
Waxman-Bahcall fluxes:		
Waxman, Bahcall 1999, evolved sources [12]	1.37	42
Waxman, Bahcall 1999, standard [12]	0.49	19

- Results summary: expected 1 bkg event, saw 3 events
  - 1 of 3 is demonstrable anthropogenic, other 2 are ??
- GZK models predict 0.3 up to 25 events (1-2 events for some mainstream models

ANITA-II limits



- 2 event background “hurts” the limit, but still good improvement over ANITA-I
- ANITA-III should start to eliminate many standard GZK models, or begin to detect them!
- Minimal fluxes are a real problem!

Summary

- Major lessons learned from ANITA:
  - Don’t deploy until EVERYTHING is ready (even if it means a scrub)
    - ANITA-2 almost had to delay a year while we sorted it out – we were prepared to scrub if we had to
  - **Calibrate everything** twice, and then one more time for good measure, before deploying it.
  - Then **Calibrate again** during operation with some other independent technique. You will never know what science you may have killed with a poor calibration
  - **Don’t underestimate the power of radio interferometry!**