Observation of deep, distant impulsive RF transmitters by the Askaryan Radio Array

John Kelley*, Ming-Yuan Lu, University of Wisconsin–Madison
David Besson, University of Kansas
David Seckel, Yue Pan, University of Delaware
for the ARA Collaboration

July 14, 2017, 35th ICRC, Busan, Korea
*speaker
Neutrino / Cosmic Ray Connections

• Can neutrinos reveal origins of ultra-high-energy cosmic rays?

• Cosmogenic neutrino flux on CMB ($E_\nu \sim 10^{18}$ eV)

• Neutrinos generated in accelerator region on photon background or in hadronic interactions ($E_\nu \sim 10^{15}$ eV)

\[
p\gamma \rightarrow p\pi^0, np\pi^+
\]
\[
\pi^+ \rightarrow \mu^+ + \nu_\mu
\]
\[
\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu
\]
Radio Detection of Neutrinos

- Many km$^2$ target needed for ultra-high-energy neutrino detection

- Neutrino-induced showers in dense media produce broadband radio pulses (Askaryan effect)
  - detectable by radio antennas

- Ice is RF-transparent and plentiful in Antarctica
  - O(km) attenuation lengths
  - ANITA (balloon), ARIANNA (Ross ice shelf), ARA (South Pole)
Askaryan Radio Array (ARA)
ARA Station Layout

- currently deployed
- 2017–18 deployment

South Pole Station

IceCube Testbed

Skiway

2 km
Optics in South Pole Ice

- Index of refraction a function of depth (firm layer)
- Radio waves bend away from surface
- Multiple paths possible
  - quasi-direct (QD)
  - quasi-reflected (QR)
Deep Calibration Pulsers

ARA-2 top view

Vpol pulsers in IceCube holes
Raytraced Radio Paths

Direct and refracted rays from IC–1 to ARA–2 (center)

- 252 ns
- 69.8 m
- Total propagation time ~ 22 μs

ARA-2

IC-1 pulser

3.6 km

1.4 km
Deep Pulser Event (IC-1 to ARA-2)

both pulses observed: QD (upgoing) and QR (downgoing)
Timing Analysis via Cross-correlation

• Time-difference analysis via cross-correlation of antenna signals
  – four QD/QR pairs
  – peaks of Hilbert envelope

• Observations consistent with ice model raytracing
Directional Reconstruction (QD only)

- cross-correlation reconstruction of QD pulses
  - sum of CC pairs for all directions in sky
  - see also M.-Y. Lu NU080, JK poster

- O(degree) directional resolution
  - distance reconstruction very difficult due to near-plane-wave timing
Distance Reconstruction with Both Pulses

- QD+QR: stereoscopic view of event allows vertex reconstruction

- Distance resolution of $O(100)$ m

- Next step — event-by-event reconstruction
  - improvement in angular resolution also expected
fraction of Hpol arrives ~30 ns early (also on-time cross-polarization)
Birefringence

- consistent time delay across events, antenna pairs

- evidence of birefringence
  - previously observed with near-vertical pulses in deep ice 
  - order-of-magnitude of effect reasonable ($\sim 10^{-3}$)

- next steps: fully understand and model this effect

---

$^\S$Kravchenko et al., Astropart. Phys. 34, 10 (2011)
SPICE Hole Logging (2018)

- two calibration pulsers lowered into ice core hole to 1700m in January 2018
- observation by 6 ARA stations + ARIANNA-like surface station
- test n(z), birefringence, firn shadow model
  - layering / horizontal propagation?
Conclusions

- Observation of deep calibration pulser events in ARA
  - validates ice model, geometric optics paradigm

- Reflected pulses allow distance reconstruction of distant event
  - close events via direct ray timing (wavefront curvature)

- Evidence of birefringence from Hpol signals
  - potentially another handle on vertex distance

- SPICE hole logging planned for this pole season
  - refine model of index of refraction vs. depth
  - birefringence vs. depth, ice flow
Backup
Previous Measurements
Hpol/Vpol Cross-Correlations

- Peak V–H correlation vs expected
- s1:tv, s1:th, rays: (QD, QD)
- Peak V–H correlation vs expected
- s2:tv, s2:th, rays: (QD, QD)
- Peak V–H correlation vs expected
- s3:tv, s3:th, rays: (QD, QD)
- Peak V–H correlation vs expected
- s4:tv, s4:th, rays: (QD, QD)
- Peak V–H correlation vs expected
- s1:bv, s1:th, rays: (QD, QD)
- Peak V–H correlation vs expected
- s2: bv, s2: bh, rays: (QD, QD)
- Peak V–H correlation vs expected
- s3: bv, s3: bh, rays: (QD, QD)
- Peak V–H correlation vs expected
- s4: bv, s4: bh, rays: (QD, QD)
- Peak V–H correlation vs expected
- s1:tv, s1: th, rays: (QR, QR)
- Peak V–H correlation vs expected
- s2:tv, s2: th, rays: (QR, QR)
- Peak V–H correlation vs expected
- s3:tv, s3: th, rays: (QR, QR)
- Peak V–H correlation vs expected
- s4:tv, s4: th, rays: (QR, QR)
- Peak V–H correlation vs expected
- s1: bv, s1: bh, rays: (QR, QR)
- Peak V–H correlation vs expected
- s2: bv, s2: bh, rays: (QR, QR)
- Peak V–H correlation vs expected
- s3: bv, s3: bh, rays: (QR, QR)
- Peak V–H correlation vs expected
- s4: bv, s4: bh, rays: (QR, QR)