Calibration, Performance, and Cosmic Ray Detection of ARIANNA-HCR Prototype Station

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Radio Detection of Air Shower induced by Cosmic Ray

- Precise measurement of energy and shower maximum
  - LOPES, CODALEMA, AERA, LOFAR, Tunka-Rex, etc.
  - mainly in 30-80 MHz, with external trigger for cross-calibration

- Standalone radio observatories for detecting UHE neutrinos, e.g., ANITA and ARIANNA in Antarctica have shown capability of hunting (UHE)CRs and measuring flux
  - around 100–1000 MHz

H. Schoorlemmer et al., Astropar. Phys. 77 (2016) 32
S. Barwick et al., Astropar. Phys. 90 (2017) 50

F. Schröder, Prog. Part. Nucl. Phys. 93 (2017) 1
Concept of ARIANNA-HCR Station

- Complementary to in-ice ARIANNA stations, more sensitive to
  - inclined UHECR
  - Mountain-skimming $\nu_\tau$

Latest result on ARIANNA-HRA:
$\nu$: C. Persichilli, PoS(ICRC2017)977
CR: A. Nelles, PoS(ICRC2017)399

Simulation on $\nu_\tau$ detection
J. Nam & T.C. Liu, PoS(ICRC2017)944
ARIANNA Horizontal Cosmic-Ray (HCR) Prototype Station

- Deployed in 2016/12
- Rx: 4 log-periodic dipole antennas (LPDA): 3 Hpol + 1 Vpol
  - H-pol: $\parallel \vec{v} \times \vec{B}$, event reconstruction
  - V-pol: polarization analysis
- with other system same as HRA station
- Goal:
  1. Test construction & robustness
  2. Long-term RF background survey
  3. Detect and characterize inclined CR
  4. Investigate the potential of $\nu_\tau$ detection
System Overview

- **LPDA**
  - high directivity: 6-8 dBi
  - broadband: 140-1000 MHz
  - 3dB beamwidth ~±40°

- **100-500 MHz bandpass filter + low noise amplifier**

- **DAQ:**
  - 1 GSample/s, 256 sample/channel
  - Trigger:
    1. channel level: dual-side threshold
    2. station level: 2-out-of-4 channel coincidence
    3. level 1 (L1) trigger for rejecting CW
    4. forced trigger every 100 s

- **Wi-Fi & Iridium satellite communication**

- **Low power consumption ~4W**

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S. Barwick et al., Astropar. Phys. 90 (2017) 50
Operation & RF background

- Acquiring data continuously until 2017/04
  - except intentional stop ~5 days
  - live time ~72.5 days (+ ~10 not transferred)
- Event rate: $10^{-3}$-1 Hz in a day
  - ~10 Hz during most noisy periods
- Forced-trigger events:
  - variation of Galactic noise is observed
  - quiet background except a few transient narrow-band (CW) noise

![Graphs showing RF survey in 2015](image)

Max coincides with ATC active
Major noise events

- **air traffic control (ATC, > 40%)**
  - around 240-280 MHz
  - wave-packet like
  - medium to high correlation
  - usually clustered in time

- **high-wind (> 30 %)**
  - correlated with storms (periods of high wind > 15 m/s)
  - power: one channel >> others
  - high power at stop band
  - clustered in time (few hour~ days)

Both noises have clear characteristics for rejection
Calibration with HiCal-2 Balloon-borne Transmitter

- HiCal-2 experiment for ANITA-4 in 2016/12
  - pulsing every ~5s, GPS recording time and location
  - 2 flights launched, entering FOV during ascending
  - distance to HCR: 80-250 km

- Event reconstruction using interferometric technique with 3 Hpol pairs

- Station orientation calibrated

- Angular resolution
  - azimuth: 1.4°
  - elevation: 0.6°

P. Gorham et al., J. Astron. Instrum. 6 (2017) 174

(reflective interference corrected)
Interference from Reflected Signal

- Below $\sim 10^0$ elevation, events get mis-reconstructed to lower angles.
- Due to increasing reflection coefficient, antenna spacing, and system impulse response (LPDA + filter)
- The angle is recovered by deconvolution
  - to be implemented to data analysis
- Crucial for distinguishing inclined cosmic rays from $V_\tau$

- $c\Delta t = 2h \sin E$
  - $h = (1.5, 4) \text{ m}, E = 5^0$
  - $\Delta t = (0.9, 2.3) \text{ ns}$
Preliminary Cosmic Ray Search of HCR Prototype Station

- Nearly vertical geomagnetic field
  - highly polarized: $\text{Hpol} > \text{Vpol}$

- Broad band spectrum decreasing with increasing frequency
  - band power excess at 140-230 MHz

- Far source & close antennas
  - similar signal strength over Hpol
  - high cross-correlation between Hpol

- Band power ratio
  - $P(140, 230) / P(60, 110)$ → reject high-wind events
  - $P(140, 230) / P(240, 280)$ → reject ATC events

- Rare event
  - time cluster cut
## Summary of Event Selection

**Data:**

<table>
<thead>
<tr>
<th>Event Selection Step</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016/12/13 12:00Z – 2017/04/13 03:00Z</td>
<td>559,700</td>
</tr>
<tr>
<td>Total number of events</td>
<td>559,700</td>
</tr>
<tr>
<td>After removing L1 event (CW, $L&lt;0.3$)</td>
<td>531,627</td>
</tr>
<tr>
<td>After ATC: $P(140,230)/P(240,280)$ cut</td>
<td>148,872</td>
</tr>
<tr>
<td>After top/bot &amp; left/right Hpol power ratio cut</td>
<td>42,504</td>
</tr>
<tr>
<td>After top/bot &amp; left/right Hpol Vp ratio cut</td>
<td>14,123</td>
</tr>
<tr>
<td>After $P(140,230)/P(60,110)$ cut</td>
<td>3,940</td>
</tr>
<tr>
<td>After Vpol-Hpol ratio cut</td>
<td>1,945</td>
</tr>
<tr>
<td>After correlation coefficient (&gt;0.5), elevation (&gt;10°), time cluster cut (100 sec) cuts</td>
<td>68</td>
</tr>
</tbody>
</table>

**Estimated live time (# of forced-trigger x 100s):** 62.1 days

*(incomplete data, ~10 day not available)*

*(Ongoing) Full simulation is required for studying selection efficiency.*
After all the cuts....

- 68 CR candidates in 62.1 days

(incomplete data)
Ongoing work

- Detailed modeling of antenna response
- Reducing errors in timing offset of each channel and spatial position of LPDA.
- Reconstruction with reflection interference deconvolved
- Template matching technique as alternative
- Calculate cosmic-ray acceptance
- Searching coincidence between HCR and HRA stations

- A new station will be deployed in 2017
  - extend LPDA bandwidth to 100-500 MHz → higher sensitivity
  - 8 LPDAs on 3 separate towers → higher angular resolution
  - Calibration transmitter at Mt. Discovery
Summary

- ARIANNA-HCR prototype station has been deployed and working properly, live time > 72.5 day
- Quiet RF background above the ice
- Calibration with HiCal-2 shows capability of event reconstruction
  - reflection interference should be considered for distinguishing inclined cosmic-ray or Earth skimming $\nu_\tau$
- Preliminary search found 68 cosmic-ray candidates in 62.1 day data
- Improved analysis is ongoing and a new station will be deployed in this year.
Backup
RF survey in 2015
HCR LPDA Response (E-plane scan)

- agreement between measured and simulated beam pattern of single antenna

- asymmetric response between left and right Hpol's in HCR config.
  - >3dB difference above 20°
  - due to interference of nearby metal structure
  - +: point to east
  - -: point to west
Simulation of Reflective Interference

Cross-correlation between Hpol pairs

Timing error of each Hpol pair

Received power (140-230 MHz)
HiCal events after deconvolving reflection effect

(before correction for interference)

HiCal-2a elevation

(expected (GPS)
reconstructed
time (UTC))

Bottom Hpol (east)-Bottom Hpol (west)

Top Hpol-Bottom Hpol (west)

Top Hpol-Bottom Hpol (east)

Fresnel (power)

$n_1 = 1, n_2 = 1.3$

Hpol

before deconvolution
after deconvolution
Projected sensitivity and event rates

Sensitivity curve assumed:
- 5 years operation with 90% duty cycle
- Using 10 dBi antennas for 120-500 MHz
- 500 stations with over 500km² area pointing Mt. Discovery and Mt. Morning

Event rate map assume:
- GZK ESS flux model [19]
- 5 years operation
- 500 stations in the same location

from poster of J. Nam & T.C. Liu, PoS(ICRC2017)944

preliminary
Timing Resolution study with Heartbeat pulser

- **stationary ground-based transmitter**
  - constant time difference of arrival btw. pair
- waveform: 10x interpolation
- cross-correlation to find TDOA
- resolution <100 ps
- Vpol channel not included yet
Selection cuts

Data in Jan., 2017

thermal trigger
forced trigger
high xcor CR candidates

\[ P_{\text{bot}, \text{avg}} / P_V (\text{dB}) > 4\sigma \text{ of forced triggered} \]
reject thermal, CW (unless Hpol dom.)

\[ \left| \frac{P_{\text{top} H} - P_{\text{bot} H, \text{avg}}}{P_{\text{top} H} + P_{\text{bot} H, \text{avg}}} \right| < 0.5 \]
reject high-wind events

\[ -0.5 < \frac{P_{\text{Left} H} - P_{\text{Right} H}}{P_{\text{Left} H} + P_{\text{Right} H}} < 0.5 \]
reject high-wind events

\[ P_{(140,230)} / P_{(60,110)} (\text{dB}) \]

Hpol: > 1.5 dB
Vpol: < 4\sigma of forced triggered
reject high-wind events

\[ P_{(140,230)} / P_{(240,280)} (\text{dB}) \]

Hpol: > 2 dB
Vpol: < 4\sigma of forced triggered
reject ATC events