The Radio Technique and Exploration of the Extreme Energy Universe

1. Background – Radio Detection of UHE neutrinos
2. ANtarctic Impulsive Transient Antenna (ANITA)
3. Tera-ton Initiatives (AURA, SalSA, ARIANNA)
4. Enabling Technologies for Extensive Arrays

Gary S. Varner
University of Hawai‘i
What I won’t cover

• Motivation
  \( \nu \) as messenger \((5+2)\), GZK flux \((6+2)\)

• Discovery potential
  – Cross-section Exotica (many)
    \( \nu \) flavor ratios \((3+1)\)

• Atmospheric showers
  – Coherent emission (Heino Falcke)
  – In-/quasi-coherent C/Ku band emission
1960’s: Askaryan predicted that the resultant compact cascade shower (1962 JETP 14, 144; 1965 JETP 21, 658):

- would develop a local, relativistic net negative charge excess
- would be coherent ($P_{rf} \sim E^2$) for radio frequencies
- for high energy interactions, well above thermal noise
- detectable at a distance (via antennas)
- polarized – can tell where on the Cherenkov cone
Where to Look?

• Salt
  – Salt domes

• Ice
  – In situ (RICE)
  – Overflight (FORTE, ANITA-lite)

• Silica sand
  – Lunar regolith (GLUE)
Goldstone Lunar Ultra-high energy neutrino Experiment (GLUE)

- Total of 120 hrs (clean) livetime [MER priority since August 2002]


- No events in high-threshold analysis
Saltzberg, Gorham, Walz et al. PRL 86 2802 (2001)

Askaryan Confirmation: SLAC T444 (2000)

- Use 3.6 tons of silica sand, brem photons to avoid any charge entering target
  ==> no transition radiation
- Monitor all backgrounds carefully
  - but signals were much stronger!
Shower profile observed by radio (~2GHz)

- Measured pulse field strengths follow shower profile very closely
- Charge excess also closely correlated to shower profile (EGS simulation)
- Polarization completely consistent with Cherenkov—can track particle source

Sub-ns pulse, $E_p \sim 200$ V/m!
Askaryan in Salt: SLAC T460

- Target: 6 tons of Morton brick salt
- Provide shower volume and embedded antenna matrix
- Antennas sample 21 grid-points along shower, dual polarization
RF Coherence vs. energy & frequency

- Much wider energy range covered than previously: 1PeV up to 10 EeV
- Coherence (quadratic rise of pulse power with shower energy) observed over 8 orders of magnitude in radio pulse power
- Differs from actual EeV showers only in leading interactions ==> radio emission almost unaffected
Why so Hard?? The Flux Problem

- At $E > 10^{20}$...

$$\int \int \int dq_f d\phi d\theta_{r,\phi,\theta}$$

1 per m² per second

"knee" 1 per m² per year

"ankle" 1 per km² per year
ANITA concept

Antarctic Ice at $f<1$GHz, $T<-20$C:

- Lossless RF transmission
- Minimal scattering
- largest homogenous, RF-transmissive solid mass in the world
- RF quiet!

Target $\sim 1$M km$^3$
Ice RF clarity: ~1km(!) attenuation length

Typical balloon field of view

~4km deep ice!

Effective "telescope" aperture:
- ~250 km³ sr @ 10^{18} eV
- ~10^4 @ km³ sr 10^{19} eV
  (compare to ~1 km³ at lower E)
Flight options

10-15 days/circuit “flight”
45 days (3 times around)
Flight Payload Design

A radio “feedhorn array” for the Antarctica Continent

- Quad-ridged horn antennas provide superb impulse response & bandwidth (200-1200 MHz)
- Interferometry & beam gradiometry from multiple overlapped antenna measurements

~7m

~320ps Measured
Signal/Background – Time Domain

- Signal
  - Vertical
  - Horizontal
  - Time [ns]

- Thermal Noise
  - Vertical
  - Horizontal
  - Time [ns]

- Impulsive Background
  - Vertical
  - Horizontal
  - Time [ns]
Frequency Domain Analysis

Signal

Radio Noise

Antropogenic

Frequency [GHz]

Amplitude [dB]

Time

Frequency

Amplitude

$\sin(\omega t)$
Major Hurdles

• No commercial waveform recorder solution (power/resolution)

• $3\sigma$ thermal noise fluctuations occur at MHz rates (need $\sim 2.3\sigma$)

• Without being able to record or trigger efficiently, there is no experiment
Trigger Reduction

Raw Signals

Level-1
Antenna

3-of-8

Level-2
Cluster

2-of-5

Level-3
Phi

2-of-2

Prioritizer
(+compress)

80 RF channels
@ 1.5By * 2.6GsA/s
= 312 Gbytes/s

100-200kHz
@ 36kBy/evt
= 3.6-7.2Gby/s

Few kHz
@ 36kBy/evt
= 0.36-0.72Gby/s

5-10Hz
@ 36kBy/evt
= 180-360kBy/s

0.25-0.5Hz events/disk

No guarantee will ever see disk again,
TDRSS uplink 5-6kbit/s
ANITA Payload Assembly

• (Engineering payload)
T-486 [Ice!]
ANITA on the End Station A beamline (June 2006)

- 32 QR horns
- 4 discones
- 4 bicones
- 8 monitor antennas
- 72 (288) channels RF digitizer & 256 channels trigger (self-triggered)
10 tons ice

David Goldstein – WG 7
Impulse response

mV

ns

Power
Askaryan Coherence

\[ P \sim E^2 \]

\[ E = 28.5 \text{GeV} \times \text{bunch q} \]

Preliminary
Timing vs Angle (with Impulse Calibration Radio Signal)

TX Up by 1.56 m

Vertical Angle Dependency

TX Down

Jiwoo Nam
UC Irvine

80ps

Expected time delay

Impulse signal from Ground Calibration TX

t2_expected

t1_expected

dt_expected = t1_expected - t2_expected

dt = dt_observation - dt_expected

150ps

Expected time delay

Face to TX

Horizontal Angle Dependency

Off by 1 Antenna
ANITA as a neutrino telescope

- Pulse-phase interferometer (150ps timing) gives intrinsic resolution of $<1^\circ$ elevation by $\sim 1^\circ$ azimuth for arrival direction of radio pulse.

- Neutrino direction constrained to $\sim <2^\circ$ in elevation by earth absorption, and by $\sim 3-5^\circ$ in azimuth by polarization angle.
Where we might be in few years...

- **IceCube**
  - Discovery of bottom-up sources
  - Discovery of ~3 GZK neutrinos

- **ANITA:**
  - Discovery of ~10 GZK neutrinos

- **Auger**
  - Discovery of a few GZK neutrinos
Saltdome Shower Array (SalSA) concept

- Rock salt can have extremely low RF loss, as radio-clear as Antarctic ice
- ~2.4 times as dense as ice
- Typical: **50-100 km³** water equivalent in top ~3.5km => **300-600 km³ sr w.e.**
Basic string architecture

Node = 12 antennas and center housing

String
12 nodes

Power

Breakout

Ping

NEMA 3R
38" x 21" x 17"

armor
tape
Insulated conductors
Stainless tube
Fibers
GEISER Data flow [NIM A554 (2005) 437-443]  
(Giga-bit Ethernet Instrumentation for SalSA Electronics Readout)

• **GEISER approach:**  
  - Digitize the “mud” in downhole  
  - ‘Pan for gold’ at the surface

• **Node/string time stamps**  
  - Allow global trigger  
  - Initiate full array data dump

---

**Digital Cell system for data collection**

**Internal FPGA:**  
- Logic, Buffer

- **RF in Continuous**

- **asic digitizer**

- **antennas**

- **In salt**

- **Hold event if >2.4s**

- **64kb/event**  
  - 1.6kHz (100baseT)  
  - 16kHz (Gbit Ethernet)

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**Trigger packets sent via FM/local radio**

- **Node/ String Time stamps**

- **Event request**

- **Final Data Transfer**

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**Central control & Global Trigger station**
SalSA simulations

- A 2.5 km$^3$ array with 225 m spacing, $12^2=144$ strings, $12^3=1728$ antenna nodes, 12 antennas per node, dual polarization $=>$ $V_{\text{eff}} \Omega = 380$ km$^3$ sr w.e. at 1 EeV

- Threshold $<10^{17}$ eV, few 100s antennas hit at 1 EeV, >1000 hits at 10 EeV

- Rate: at least 20 events per year from rock-bottom minimal GZK predictions

PRD 72 (2005) 023002
Angular resolution

- Of order 1 degree angular resolution required for neutrino cross section measurements
- Studied in detail for 12x12 string array, using Chi-squared minimization
- For GZK energies:
  - $0.1^\circ$ achieved for contained events--inside the array
  - $1^\circ$ achieved for external events, parallel to face, 250 m outside of array (partial Cherenkov cone seen)
- Polarization information + unscattered Cherenkov cone leads to excellent angular resolution!
Potential Future Sensitivity

- Compared with handful of events

- SalSA 3 yrs live
- 60-230 GZK neutrino events
If we don’t change course, we’ll end up where we’re headed

-- Chinese Proverb
ARIANNA - A New Concept for Neutrino Detection

ARIANNA Institutions: UCI, UCLA, UH, OSU, UC-London

Steve Barwick – WG 7
Satellite Image of Victoria Land and Ross Ice Shelf

Dry Valleys

ARIANNA
30x30 km²

Ice Thickness
~500m

Minna Bluff

~150 km

100 x 100 array

Ross Island

south
Reflected and Direct Events

S. Barwick, 3rd NOVE Workshop (Venice, 2006)

Direct

Reflected
(much greater solid angle)
Protostation

Block Diagram of Electronics

ANITA & AUGER technology
AURA
(Askaryan Under-ice Radio Array)
A Successor to RICE and Prelude to a 10-km scale Neutrino Detector
RICE $\Rightarrow$ AURA

- Deployed with AMANDA
- Challenging EMI backgrounds
IceCube Opportunity ➔ Impact

Existing RICE

Utilize IC DAQ/Control Infrastructure
- Stay below firn (variable index of refraction)
- Take advantage of unused IC breakouts and overlaps with IC
- Put a few shallow to take advantage of coincidences with RICE
Radio, acoustic have long reach, can be much sparser, shallower, and smaller diameter holes.

R&D Emphasis
1. Lower amplifier costs
2. Lower trigger costs
3. Extend sensitivity

Justin Vandenbroucke – WG 7
Particle ID/Hybrid Detector Trigger

- Charged/neutral current & flavor ID enhanced with subthreshold samples
- Coincidence with optical (lower E threshold [PeV])
- Phased array – can push well down into the noise
- **Challenge**: for multi-k antenna array, multi-Terasamples/s
Buffered LABRADOR (BLAB1) ASIC

- 64k samples deep
- Multi-MSa/s to Multi-GSa/s
- Local/Global readout mode
- 32-64us to form Global trigger
- See WG7 for details

3mm x 2.8mm, TSMC 0.25um

Just to show not “pie in the sky”
RF/Optical complementarity

- Radio: 0.1–1 GHz, $T_{\text{rms}}=300K$
- Dipole antenna
- $L_{\text{ATTEN}}=500m$
- Optical: 330–450 nm
- $\phi 8''$ photomultiplier
- $L_{\text{ATTEN}}=50m$

Graph showing detected cascade photons at 100m vs. optical.

- RF signal, $d=100m$
- Optical signal, $d=100m$
- RF signal, $d=500m$
- Optical signal, $d=500m$
- rf noise floor
- opt noise floor = Spa
- Cascade

Graph axes:
- Detected cascade photons at 100m vs. optical
- Cascade energy (eV)
- Logarithmic scale

Images:
- Old man holding a phone
- Young woman holding a modern phone
A Sobering Word

- **ANITA**
  - Balloon experiments are risky business
  - EMI backgrounds (ANITA-lite OK, but...)

- **AURA**
  - IceCube itself, EMI backgrounds

- **ARIANNA**
  - Ice/sea boundary at higher frequencies

- **SalSA**
  - Drilling
  - Attenuation length, inclusions, volume saturates
The next year will be very exciting:

- **ANITA** first to probe the “guaranteed” GZK flux
  - Successful *ice-target* calibration run in June
  - First flight in December

- **Tera-ton Detector** enabled by low-cost, low-power RF developments:
  - **SalSA**
    - Salt mine attenuation measurements
  - **AURA**
    - Deploy 4 antenna clusters this year
  - **ARIANNA**
    - Deploy prototype station this year
Back-up slides
Neutrinos: The only known messengers at PeV energies and above

- **Photons lost above 30 TeV:** pair production on IR & μ wave background
- **Charged particles:** scattered by B-fields or GZK process at all energies
- Sources extend to $10^9$ TeV!
- => Study of the highest energy processes and particles throughout the universe requires PeV-ZeV neutrino detectors
- To **guarantee** EeV neutrino detection, **design for the GZK neutrino flux**
(Ultra-)High Energy Physics of Cosmic rays & Neutrinos

- Neither origin nor acceleration mechanism known for cosmic rays above $10^{19}$ eV

- A paradox:
  - No nearby sources observed
  - Distant sources excluded due to process below
Expectations:

1. Greisen, Zatsepin, Kuzmin (GZK) calculated a cutoff: \( p \ast \gamma \rightarrow \Delta \rightarrow n + \pi \rightarrow \nu \)

2. These interactions produce a corresponding neutrino flux

3. Provides a handle on what is going on for these “extra-GZK” events
Askaryan Signature

- Significant signal power at large frequencies
- Strong linear polarization (near 100%)
T460 rock-salt target

- 4lb high-purity synthetic rock-salt bricks (density=rock salt)
- + some filler from local grocery store...

- Beam exit point shown above
- Depth ~ 15 radiation lengths
  - Shows some deposits from spallation, good indicator of transverse size of shower!
Major Hurdles

• No commercial waveform recorder solution (power/resolution)

• $3\sigma$ thermal noise fluctuations occur at MHz rates (need $\sim 2.3\sigma$)

• Without being able to record or trigger efficiently, there is no experiment
Strategy: Divide and Conquer

- Split signal: 1 path to trigger, 1 for digitizer
- Use multiple frequency bands for trigger
- Digitizer runs ONLY when triggered to save power
ANITA Level 1 – 3 of 8 Antenna

Plot of Frequency versus Signal Power to the Tunnel Diode input for SHORTv2.
Diode detector Response

\[ 2.3\sigma \approx 3.9 \frac{P}{<P>} \]

Well sub-nanosecond

Needs amplification!

Fast PMT-like
ANITA local trigger

- Multi-band triggering essential to ANITA sensitivity
- Methods proven by FORTE, GLUE experiments
- Exploits statistical properties of thermal noise vs. linear polarization for signal
- Signal: most or all bands; noise: random
- 5 of 8 shown here -- 3 of 8 is found to be enough
Trigger Reduction

Raw Signals

Level-1
Antenna
3-of-8

Level-2
Cluster
2-of-5

Level-3
Phi
2-of-2

Prioritizer
(+compress)

80 RF channels
@ 1.5By * 2.6GSa/s
= 312 Gbytes/s

100-200kHz
@ 36kBy/evt
= 3.6-7.2Gby/s

Few kHz
@ 36kBy/evt
= 36-72Mby/s

5-10Hz
@ 36kBy/evt
= 180-360kBy/s

No guarantee will ever see disk again,
TDRSS uplink 5-6kbit/s
Large Analog Bandwidth Recorder and Digitizer with Ordered Readout [LABRADOR]

- 8+1 chan. * 256+4 samples
- Common STOP acquisition
- 3.2 x 2.9 mm
- Conversion in 120µs (all 2340 samples)
- Data transfer takes 80µs
- Ready for next event in 200µs

- Switched Capacitor Array (SCA)
- Massively parallel Wilkinson ADC array

Random access:

Straight Shot RF inputs
GHz Bandwidth “oscilloscope on a chip”

Transient Impulse

 FFT Difference

\[ f_{3dB} \rightarrow 1.2\text{GHz} \]
LAB3 Architecture Details

LABRADOR(3) architecture

- No missing codes
- Linearity as good as can make ramp
- Can bracket range of interest
High Speed sampling

PMT pulse comparison

<table>
<thead>
<tr>
<th></th>
<th>LABRADOR</th>
<th>Commercial</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sampling speed</strong></td>
<td>1-3.7 GSa/s</td>
<td>2 GSa/s</td>
</tr>
<tr>
<td><strong>Bits/ENOBs</strong></td>
<td>12/9-10</td>
<td>8/7.4</td>
</tr>
<tr>
<td><strong>Power/Chan.</strong></td>
<td>&lt;= 0.05W</td>
<td>5-10W</td>
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</tbody>
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Particle Physics: Energy Frontier

- GZK $\nu$ spectrum is an energy-frontier beam:
  - up to 300 TeV center of momentum particle physics
  - Search for large extra dimensions and micro-black-hole production at scales beyond reach of LHC
  - $\nu$ Lorentz factors of $\gamma=10^{18-21}$

![Graph depicting $\sigma$ vs $E_\nu$ for different models and scales.](image-url)
Particle Physics: Neutrinos

- GZK neutrinos are the “longest baseline” neutrino experiment:
  - Longest L/E (proper time) for:
    - sterile $\nu$ admixtures &
    - anomalous $\nu$ decays
  - SUN: L/E $\sim 30$ m/eV
  - GZK: L/E $\sim 10^9$ m/eV

- Measured flavor ratios of $\nu_e: \nu_\mu: \nu_\tau$ can identify non-standard physics at source

$\nu_e: \nu_\mu: \nu_\tau$ (1:1:1)! (5-6):1:1

Neutrino decay leaves a strong imprint on flavor ratios at Earth
Cherenkov polarization tracking

- Radio Cherenkov: polarization measurements are straightforward

- Two antennas at different parts of cone:
  - Will measure different projected plane of E, S

Cherenkov radiation predictions:
- 100% linearly polarized
- plane of polarization aligned with plane containing Poynting vector $\mathbf{S}$ and particle/cascade velocity $\mathbf{U}$
  - Intersection of these planes defines shower track
Polarization tracking

- Measured with dual-polarization embedded bowtie antenna array in salt
SalSA Physics Menu

• Astro-physics
  – Detection/observation of HE $\nu$ sources

• Cross-section
  – Test with precision SM well above LHC cm energies
  – Deep inelastic $\nu$-n probing $\rightarrow$ high energy $\nu$ “beam”

• Particle ID
  – 1:1:1 ?
  – CC/NC ratio ?

• Others?
Estimated SalSA Energy threshold

- Ethr < 300 PeV (3 x 10^{18} eV) best for full GZK spectral measurement

- Threshold depends on average distance to nearest detector and local antenna trigger voltage above thermal noise
  - \( V_{\text{noise}} = k T \Delta f \)
  - \( T_{\text{sys}} = T_{\text{salt}} + T_{\text{amp}} = 450K \)
  - \( \Delta f \) of order 200 MHz

- 225 m spacing gives 30 PeV
- Margin of at least 10x for GZK neutrino energies
Interaction/PID

Ped Miocinovic (UH)
Buffered LABRADOR (BLAB1) ASIC

Measured Noise

- 10 real bits of dynamic range
- A few fixes (lower power, higher BW)
- BLAB2 when have money

1.4mV

1.8V dynamic range

-3dB ~300MHz