The challenges in the acoustic detection of ultra-high energy neutrinos

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(Stanford U./UHM, Dept. of Physics and Astronomy),
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Team: Justin Vandenbroucke, Giorgio Gratta (Stanford U.)
Talk layout

1. Short introduction
2. Theoretical simulation of neutrino acoustic signal
3. Description of experiment
4. Lightbulb calibration
5. Data and types of events
6. Detection of neutrino acoustic signal in coherent noise
Ultra High Energy (UHE) Neutrino Sources 
($\geq 10^{18}$ eV)

Hypothetical sources (biggest):
- gamma ray bursts,
- active galactic nuclei,
- decay of heavy objects ("top-down" mechanisms).

Also (smaller):
- galactic mechanisms (from cosmic ray interactions with baryons),
- Greisen-Zatsepin-Kusmin mechanism (reaction of protons of energy >$5 \times 10^{19}$ eV with cosmic microwave background radiation).

Very small:
- atmospheric background.

Measured UHE Cosmic Ray fluxes:
$\sim 100 \text{ km}^{-2} \text{y}^{-1}$ above $10^{18}$ eV,
$\sim 1 \text{ km}^{-2} \text{y}^{-1}$ above $10^{19}$ eV,
$\sim 1 \text{ km}^{-2} \text{century}^{-1}$ above $10^{20}$ eV.
Previous work on acoustic detection of UHE neutrinos

- Acoustic detection was first proposed by Askarjan in 1957
- DUMAND (project was not realised)
- Sulak et al. (1979) - experimental measurements of sound production by 150 MeV - 28 GeV proton beams in water
- Baikal Neutrino Project (Domogatsky, unpublished talk, presented at Neutrino 2000):

![Diagram of EAS array and hydrophone setup and sample of registered signal]
Neutrino-induced shower in water (1)

1. Are created by collision with nucleons

   Butkevich et al., 1998:
   neutrino/antineutrino-nucleon
   antineutrino-electron

   ![Graph showing σ vs. E for νN interactions]

   ![Graph showing σ vs. E for νN interactions]

2. ~80% energy goes into lepton, ~20% into hadronic shower.
3. Muons and tau leptons (created by ν_μ and ν_τ, correspondingly) do not produce detectable acoustic showers.

   σ_{TOT(νN)}
   σ_{CC(νN)}
   σ_{NC(νN)}
Neutrino-induced shower in water (2)

- hadronic shower: short, regular

10^{20} \text{ eV hadronic shower}

- electromagnetic shower: elongated and has substructure due to Landau-Pomeranchuk-Migdal (LPM) effect (decrease of electromagnetic cross-sections in dense media)

10^{20} \text{ eV electromagnetic shower}

LPM: important for particles of E>2\times10^{15} \text{ eV}
Acoustic pulse calculations: 1. Hadronic shower

- Hadronic shower
- Hydrophone
- Ocean water
- Shower
- Surface
- Bottom
- ~1-2 km

Graphs:
(a) Pressure vs. Time
(b) Fluence vs. Amplitude vs. Angle

Pressure (Pa)
Time (μs)
Fluence (J/m²)
Amplitude (Pa)
θ (degrees)
Acoustic pulse calculations: 2. Electromagnetic shower

![Diagram showing ocean water, surface, bottom, hydrophone, and electromagnetic shower.]

(a) Pressure (Pa) vs. time (µs) for θ = 8°

(b) Amplitude (Pa) and fluence (J/m²) vs. θ (degrees) for positive and negative half pulses.
Matched filter as an optimal detection algorithm in Gaussian noise

Matched filter technique is based on maximizing the likelihood of signal presence and uses the differences in noise spectrum and signal spectrum.

The matched filter which is used is a digital filter:

\[ Y_k = \sum H_i X_{k-i} \]
The theoretical prediction of sensitivity: the false alarm rates and the efficiency

*Efficiency* is defined as the fraction of neutrinos that are detected in respect to those that interact. There are *false alarms* due to gaussian fluctuations. Both efficiency and false alarm rate are determined by the threshold. To be detectable, $\nu$ event rate has to be higher than the false alarm rate.

52 sensors, ~250 km²
solid lines: $\nu_e$
dashed lines: $\nu_\mu$ and $\nu_\tau$
The theory of Large Extra Dimensions predicts a TeV order of fundamental Planck scale. When large extra dimensions are present, a UHE neutrino interacts to create a black hole which then decays to ~10 GeV partons in CM ref. frame, or ~1000 TeV in the lab frame.
The US Navy Atlantic Undersea Test and Evaluation Center

hydrophone subset used in the experiment (set up at Bahamas by J. Vandenbroucke)

hydrophone depths are 1550-1600 m
AUTEC experiment setup

- Dell 8100 PC with 1.7 GHz Pentium 4 processor and CD writer
- National Instruments PCI-MIO-16E card with BNC 2110 interface
- Data acquisition software written in Labview 6.0
- Data are currently saved on CDs in zip format (1 CD/day)
  (in future, on a hot-swappable hard drive with FireWire interface)

Technical difficulties:
- crosstalk (~6%) between certain channels,
- spike noise (example shown later).

[Diagram of AUTEC setup with labels for DAQ PC, Hydrophones, CDROMs, and Stanford]
Hydrophone system properties

1. Transfer function

2. Variability in the gain

Relative gain inferred from noise level

before 08/27

after 08/27
Trigger algorithm

Digital filter response function

Simulated data

Filtered simulated data
Adaptive threshold

A typical run, from 2am to 2pm

The implosion calibration run
# Data file format (one file/minute)

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<th>Data</th>
<th>Type</th>
<th>Size (bytes)</th>
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<td>threshold step</td>
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<td>4</td>
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<tr>
<td>overflows since last event</td>
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<td>4</td>
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<tr>
<td>triggering index</td>
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<td>dt</td>
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<tr>
<td><strong>raw data</strong></td>
<td>2D array of sgl (179 x 7)</td>
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**TOTAL** 890.598 KB * 60 minutes * 24 hours = **1.3 GB/24 hrs** (after compression, fits on a CD-ROM)
### Current acquisition parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<td>Hydrophones in use</td>
<td>1-7 (not 8)</td>
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<td>Trigger type</td>
<td>filter</td>
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<td>Tau</td>
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<td>Response function samples</td>
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<td>ADC limits</td>
<td>0.5 V</td>
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<tr>
<td>Sampling frequency</td>
<td>max: 1250 kHz / 7 channels = 179 kHz</td>
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</tbody>
</table>
The calibration light bulbs
Lightbulb pressure data

Bulb #1

Central hydrophone

Peripheral hydrophones, reflected from the top

Pressure, Pa

Hydrophone #

1 2 3 4 5 6 7

Central hydrophone, reflected from the top

Peripheral hydrophones

Time, s

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8

-60 -40 -20 0 20 40 60
Close-up of the initial signal

Pressure, Pa vs. Time, ms

Pressure, Pa vs. Time, ms
Theoretical calculation of a pulse from a lightbulb implosion

3 cm diameter lightbulb, 150 m depth, distance 1.5 km
Spectral energy of a lightbulb pulse: theoretical prediction and experimental data
Boat (GPS) and bulb (reconstructed) coordinates
Reconstructed implosion depths

<table>
<thead>
<tr>
<th>bulb</th>
<th>depth (m)</th>
<th>P (kPa)</th>
<th>E0  (J)</th>
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<tr>
<td>10</td>
<td>290</td>
<td>2846</td>
<td>427</td>
</tr>
</tbody>
</table>
Spectra from every minute for two days

Spectra from each minute from 7/30/00 midnight to 7/31/00 6pm
assuming only 1 gain

Justin Vandenbroucke
Stanford University
September 27, 2001
Wind and Noise

Wind speed at Nassau airport

Noise at each phone
Basic classification of events

Day 2001.08.04; Hour 7

- correlated 7.5 kHz noise
- other (animals, ships etc.)
- electric spike noise
Correlated noise at 7.5 kHz

Event 2001.08.04/07.00 #14, chan #0 filtered
Electric spikes (generated in the DAQ card)

Event 2001.08.04/07.02 #27, chan #5 filtered
Relative content of acoustic ("useful") and non-acoustic events

Day 2001.08.26

- Useful
- 7.5kHz spike

Noise level in 10-13 kHz, arb. units

Events/minute

Hour

0 5 10 15 20 25
August: frequency vs number of periods distribution of "useful" events.

August: 804790 events out of 1292280 (15980 minutes)
Example of event 1

Event 2001.08.04/18.00 #15, chan #1 filtered
Examples of dolphin signals recorded by AUTEC personnel
Example of event 2

Event 2001.08.04/14.42 #42, chan #2 filtered

Time, ms

Signal, Pa

Spectrum, arb. units

Frequency, kHz
Example of event 3

Event 2001.08.04/05.00 #10, chan #2 filtered

Time, ms

Signal, Pa

Spectrum, arb. units

Frequency, kHz
Example of event 4

Event 2001.08.04/05.00 #12, chan #1 filtered

Time, ms

Signal, Pa

Spectrum, arb. units

Frequency, kHz

Spectrum, arb. units
September: *frequency vs number of periods* distribution of "useful" events.

September: 1517390 events out of 2654019 (33957 minutes)

*noise from rain (?)*
Rain (?) signals

Day 2001.09.01

Event 2001.09.01/01.35 #92, chan #2 filtered

Rain (?) signals
UHE neutrino signature after AUTEC hydrophone filter
Theoretical lightbulb signature (@ 1.5 km) after filter

Experimental lightbulb signature

Theoretical lightbulb signature (@ 1.5 km) after filter
Simulated event

Event simulated #20, chan #0 filtered

Time, ms

Signal, Pa

Spectrum, arb. units

Frequency, kHz
Frequency vs number of periods distribution of simulated events.

Simulated 9508 fake events (thr=0.01)

Simulated 3416 fake events (thr=0.02)
August: *frequency vs number of periods* distribution of "useful" events.

August: 804790 events out of 1292280 (15980 minutes)

- **T=1 ms limit**
- **ships**
- **simulated events**
- **spikes (by mistake)
Conclusions and current work

- the fact that AUTEC uses high-pass 7.5 kHz filter makes neutrino detection more difficult because some of the energy of the signal is contained below this frequency,

- to distinguish between some type of noise (such as 7.5 kHz noise and spike noise) and neutrino signature, a second filter is needed beside the matched filter. It will be installed during the second field trip this winter.

- to distinguish between animal signals and neutrino signature, a more elaborate filter is needed, which will take into account the phase information and directionality of the pulse.