Acoustic Detection

Giorgio Riccobene
INFN-LNS
Motivations

- UHE neutrino fluxes
- Neutrino cross section at extreme energy
Extending the neutrino observation to extreme energies

- Astrophysics: UHECR origin, GZK neutrinos
- Cosmology: Decay of Plank scale massive particles, Topological Defects, ...
- Particle physics: Study neutrino cross section
Large Area Detectors for HE neutrinos

Optical Detection (ICECUBE-KM3NeT)
- Medium: Seawater, Polar Ice
- $\nu_\mu$ (throughgoing and contained)
- $\nu_{e,\tau}$ (contained cascades)
- Carrier: Cherenkov Light (UV-visible)
- Attenuation length: 100 m
- Sensor: PMTs
- Instrumented Volume: 1 km$^3$

Radio Detection (RICE, SALSA)
- Medium: Salt domes, Polar Ice
- $\nu$ (cascades)
- Carrier: Cherenkov Radio
- Attenuation length: 1 km
- Sensors: Antennas
- Instrumented Volume: >1 km$^3$

Acoustic Detection (Prototypes)
- Medium: Seawater, Polar Ice, Salt Domes
- $\nu$ (cascades)
- Carrier: Sound waves (tens kHz)
- Attenuation length: ~10 km
- Hydro(glacio)-phones
- Instrumented Volume: >100 km$^3$
## A Short Summary of Activities on Acoustic Detection

<table>
<thead>
<tr>
<th>Year</th>
<th>Collaborations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1957</td>
<td>Askaryan, Markov Zeleznyk</td>
</tr>
<tr>
<td>1979</td>
<td>Learned, BNL, Harvard, SLAC - Beam Experiments</td>
</tr>
<tr>
<td>’80s</td>
<td>DUMAND, Kamchatka</td>
</tr>
<tr>
<td>’90</td>
<td>SADCO</td>
</tr>
<tr>
<td>2000’s</td>
<td>BAIKAL (ITEP, MSU, Irkutsk), ANTARES (Erlangen, Marseilles, Valencia), SAUND (Stanford, US Navy), ACORNE (Imperial College, Lancaster, Northumbria, Sheffield, UCL), SPATS (DESY Zeuthen, Berkeley, Gent, Stockholm, Uppsala,…), NEMO (LNS, Roma, Pisa, Genova)</td>
</tr>
</tbody>
</table>

Beam Experiment, Simulation, R&D, deep sea measurements thanks to neutrino telescopes’ infrastructures and military facilities after the end of cold war
The Thermo-Acoustic Mechanism

- Basic Theory
- Beam Test Experiments
- Neutrino Acoustic Detection
Basics of thermo-acoustics mechanism

A pressure wave is generated instantaneous following a sudden deposition of energy in the medium (neglecting absorption: O(10 km) at 10 kHz)

Instantaneous deposition of heat through ionization

\[ t_{\text{deposition}} \approx \frac{D}{c} \approx 10^{-7} : 10^{-8} \text{ sec} \]

Thermo-acoustic process:

- Increase of temperature (specific heat capacity \( C_p \)), expansion (expansion coeff \( \beta \))

\[ t_{\text{expansion}} \approx 10^{-5} \text{ sec} \gg t_{\text{deposition}} \]

\[
\nabla^2 p - \frac{1}{c_s^2} p = -\frac{\beta}{c_p} \frac{\partial \varepsilon(r,t)}{\partial t}
\]

For a point like source (micropulse):

\[ p(r,t) \propto \frac{E_0 \beta}{4\pi c_p} \frac{1}{c_s} \frac{\partial}{\partial t} \frac{\delta \left( t - \frac{r}{c_s} \right)}{r} \]

Bipolar pulse spherical expansion

For a shower heating a volume of matter (macropulse):

\[ p(r,t) \propto \frac{\beta}{4\pi c_p} \frac{1}{\partial t} \int \frac{1}{r} \varepsilon \, dV \]

Sum of pointlike sources: wavefront and signal shape depend on the energy density distribution
Accelerator Experiments: results and open questions

Brookhaven NL (Harvard, SLAC) 1979

- 200 MeV proton beam (LINAC)
- Spill time 3 to 20 us
- Beam diameter 4.5 cm
- Energy deposited in water $10^{19} \rightarrow 10^{21}$ eV
- Bipolar pulses observed
- Dependency on $C_p$, $T$ and on beam diameter confirmed (about 10% uncertainty)

Recent measurements (2000’s)

- Uppsala: 177 MeV p
  - $E = 10^{16} - 10^{17.5}$ eV
  - Bipolar pulse observed
  - Unclear dependence on temperature
  - Other contribution to observed pulses?

- ITEP Synchrotron: 100, 200 MeV p
  - $E = 10^{15} - 10^{20}$ eV
  - Measured pressure increases linearly with $E$

- Erlangen Laser Nd-YaG
  - $E = 10^{17} - 10^{19}$ eV
  - Dependence on $C_p$ confirmed

[Graphs and images related to energy deposition and measurement results]
Neutrino Acoustic Detection Principle

- Neutrino Interaction (strong Earth absorption: look upward!)
- Hadronic shower formation at interaction vertex
  \( (\nu_e \text{ e.m. shower}) \)
- H shower carries (on average) \( \frac{1}{4} E_{\nu} \)
- Shower Development
  (LPM must be taken into account for EHE)
- Sudden deposition of heat through ionization
- Thermo-acoustic process:
  Increase of temperature \( (C_p) \), Volume Expansion \( (\beta) \)
- The “pen shaped” energy deposition region (20 m depth, 10 cm diameter) produces a pancake shaped acoustic wave peak wavelength
  \[ \lambda \approx 2d \quad f = \frac{c_s}{2d} \approx 10 \text{ kHz} \]
- Acoustic wave propagation in the medium: near field
  \[ p_{\text{max}} (r) \propto \frac{1}{\sqrt{r}} \]
### Acoustic pulse amplitude in Salt, Water, and Ice

Conversion of ionization energy into acoustic energy

<table>
<thead>
<tr>
<th></th>
<th>Med Sea</th>
<th>S.P. ice</th>
<th>NaCl</th>
</tr>
</thead>
<tbody>
<tr>
<td>T [°C]</td>
<td>14°</td>
<td>-51°</td>
<td>30°</td>
</tr>
<tr>
<td>$c_s$ [m s⁻¹]</td>
<td>1545</td>
<td>3920</td>
<td>4560</td>
</tr>
<tr>
<td>$\beta$ [K⁻¹]</td>
<td>25.5x10⁻⁵</td>
<td>12.5x10⁻⁵</td>
<td>11.6x10⁻⁵</td>
</tr>
<tr>
<td>$C_p$ [J kg⁻¹ K⁻¹]</td>
<td>3900</td>
<td>1720</td>
<td>839</td>
</tr>
</tbody>
</table>

$$\gamma = \frac{c_s^2}{C_p} \beta$$

Gruneisen coefficient

$$p_{max} \approx E_v \times \frac{1}{4} \times \gamma \approx 6 \cdot 10^{-21} E_v \left[ \frac{\text{Pa}}{\text{eV}} \right]$$

in water
The Size of Neutrino Acoustic Detectors

\( E_\nu = 10^{20} \text{ eV} \)

in water: \( p = 0.6 \text{ Pa} \) @ 1 km \( \rightarrow 20 \text{ mPa} \) (neglecting attenuation)

in ice: \( p = 6 \text{ Pa} \) @ 1 km \( \rightarrow 200 \text{ mPa} \) (neglecting attenuation)

Underwater Cherenkov detectors
Upgoing events – 100 TeV

\[
P_{\nu\mu} \left( E_\nu, E_{\mu\mu}^{\text{min}} \right) = R^{\text{eff}}_{\mu} \sigma_{\text{CC}} N_A \approx 10^{-4}
\]

\[
\frac{N}{A_{\text{eff}} \cdot T} = \Phi_{\nu\mu} 2\pi e^{-D(N_A \sigma_{\text{Tot}} p_{\text{Earth}})} \approx 100 \text{ events km}^{-2} \text{y}
\]

Underwater Acoustic detectors
Downgoing events – 10^{20} eV

\[
P_{\text{det}} \left( E_\nu, P_{\text{min}} \right) = H^{\text{eff}}_{\text{det}} \sigma_{\text{Tot}} N_A \approx 10^{-3}
\]

\[
\frac{N}{A_{\text{eff}} \cdot T} \approx 10^{-3} \text{ events km}^{-2} \text{y}
\]

Sound absorption length in ocean \( O(10 \text{ km}) \), noise \( O(10 \text{ mPa}) \)

Several groups developing and improving simulation codes for large acoustic detectors
What we can do with 1 km^3 filled with hydrophones?
Study of Medium Properties
Study of the Medium Acoustic Properties: Water

Absorption is mainly caused by chemical relaxation:

- $\text{B(OH)}_3$ 50 Hz - 5 kHz
- $\text{MgSO}_4$ 5 kHz – 500 kHz

\[
a_{\text{sound}} = \left( \frac{8\pi^2\kappa}{3\rho c_s^3} \right) f^2
\]

\[L_a \approx 10 \text{ km (at 10 kHz)}\]

Sound velocity in water changes as a function of depth, temperature and salinity:

- At surface (T, S) dominated at large depth (increases linearly with pressure)
- \[c_s = 1545 \text{ m/s} \quad \frac{\Delta c_s}{\Delta z} = 1.65 \text{ cm/s/m}\]

→ refraction

pancake shape modification
Acoustic Noise in Water

Diffuse noise: Seismic, surface waves (wind), rain, thermal noise
Impulsive noise: Cetaceans, man made shipping (also diffuse!) and instrumentation

Man made noise is increasing (1 dB/year in densely inhabited seas)

Knudsen’s Formula

\[ P(f_{Hz}, SS) = 94.5 - 10 \log f^{5/3} + 30 \log (SS + 1) \]
Study of the Medium Acoustic Properties: Polar Ice

Not a well known medium... Need accurate in situ measurements!

<table>
<thead>
<tr>
<th>scattering</th>
<th>absorption</th>
<th>speed of sound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rayleigh scattering at crystal boundaries → crystal size → frequency ( \lambda_s \sim a^3 \times f^4 ) theory: ( \lambda_s(10 \text{ kHz}) = 800 \text{ km} ) ( \lambda_s(100 \text{ kHz}) = 0.2 \text{ km} )</td>
<td>molecular reorientation → energy loss in relaxation temperature dependent crystal size dependent South Pole: ( \lambda_a(200 \text{ m}) = 8 \text{ km} ) ( \lambda_a(2000 \text{ m}) = 0.8 \text{ km} )</td>
<td>weak temperature dependence strong density dep. → signal refraction important in firn pressure waves: ( v_s = 3900 \text{ m/s} ) shear waves: ( v_s = 2000 \text{ m/s} )</td>
</tr>
</tbody>
</table>

New results from SPATS

Absorption length / km

Depth / km

Sound speed (m/s)

Depth (m)

Source at 1000 m depth

Horizontal distance / m

Giorgio Riccobene LNS
Acoustic Noise in Ice

SPATS Measurements:

Noise is stable
Gaussian
Independent on weather conditions
No seasonal variation observed

Changes as a function of depth

Absolute value determination is not possible now due to change of glaciophone sensitivity with pressure and temperature.

Needs in situ calibration
Acoustic Neutrino Event Simulation
Event Reconstruction
Expected Effective Volume and Sensitivity
Simulations of neutrino interaction and shower propagation

**Neutrino Interaction**
- ANTARES (Erlangen, Marseilles)
- SAUND
- Ghandi et al.
- ACORNE
- ANIS (from Amanda)
- HERWIG + CORSIKA
- neutrino shower simulator

**Shower development**
- Zheleznyk and Dedenko (e.m. shower including LPM)
- SAUND
- hadronic
- Alvarez Muniz-Zas
- ANTARES (Marseilles)
- Hadronic + e.m.
- GEANT 4 + LPM

*Similar results for CORSIKA*
Simulations of neutrino interaction and shower propagation

Shower development

ACORNE:
CORSIKA modified for water

transverse and longitudinal energy deposits have been parameterized for fast simulations

Comparisons with GEANT:
~ 10% lower at peak
Showers broader

Comparison with NKG:
less energy at smaller radii
low frequency contribution enhanced

Acoustic Wave Propagation in Water and Ice

Based on the Learned paper 1979

Thermoacoustic model + sound waves interference

\[ \rho_{\text{max}} \sim 6 \cdot 10^{-21} \text{ Pa/eV} \]

pancake shaped wavefront

\[ 10^{20} \text{ eV proton @ 1 km} \]

ACORNE, SAUND, ANTARES (Erlangen, Marseilles)

\[ \text{Sonic pancake} \quad \text{mPa/} \text{EeV} \]

Sound velocity grandient : wave refraction
Event Detection and Reconstruction

Event trigger: ACORNE, SAUND
Matched filter on signal
(factor 3 improvement SNR)
Caveat: signal is different at different angles:
a number of matched filters should be applied
(ACORNE)
Threshold 35 mPa
(1 False alarm over 10 years for calm sea noise)
Beamforming
gain $\sqrt{N_{Hydros}}$ for white noise

Vertex Reconstruction: ACORNE, SAUND
At least 4 hydrophones required
Homogeneous medium: Exact analytical solution
Real Case (Sound Velocity Profile): Ray Tracing
Caveat: refraction and surface/bottom reflections

Event Energy reconstruction:
Estimate energy from reconstructed distance and
wavefront shape and amplitude
Acoustic Detector Effective Volume

ANTARES (Erlangen, Marseilles), ACORNE

Effective volume: \[ V_{\text{eff}} = \frac{N_{\text{det}}}{N_{\text{gen}}} V_{\text{gen}} \]

Generation volume is limited due to wave refraction and reflections on surface/bottom

**Homogeneous medium**

Sea State 0 noise < 2 mPa [10kHz to 50 kHz]
Not realistic for long term measurements

Sea State 2 noise ~ 10 mPa [10: 50 kHz]

Instrumented volume 1 km³ 400 AM

Threshold of 5 mPa or better desirable

\[ \text{Not much gain for instrumentation densities} > 200 \text{ AM/km}^3 \]

\[ 10^{20} \text{ eV} \]

\[ 10 \text{ km}^3 \]

\[ 100 \text{ km}^3 \]

\[ 10 \text{ km}^3 \]
Acoustic Detector Sensitivity

**ANTARES (Marseilles, Erlangen)**

- 1500 km³, 200 hydros per km³
- 5 years
- Threshold: 5 mPa

**ACORNE**

- 1100 hydros in 1 km³
- 1 year, threshold: 35 mPa, 95% CL (random geometry)

**km³ regular geometries**

- 5 years, 15 mPa, 95% CL
- 10 years, threshold: 5 mPa, 90% CL (random geometry)

A “complementary” km³-scale detector?
Hybrid detector in Ice

Optical:
- 80 IceCube
- 13 IceCube-Plus holes at 1 km radius (2.5 km deep)

Radio/Acoustic:
- 91 holes, 1 km spacing, 1.5 km deep

Coincident effective volumes + event rates for IceCube (I), an optical extension (O), and combinations with surrounding A + R arrays
Technological R&D

Transducers
- piezo hydrophones
- glaciophones
- fiber optic hydrophones

Calibrators
Transducers: Piezo Hydrophones

Commercial Piezo Hydrophones (for deep sea)
There is a good number of companies expert in developing hydrophones for military and navigation instrumentation. Also ceramic available on the market to build hydrophones.

Sensitivity dB re 1V/µPa
Reson TC4042 (2500m) - 195 dB +20 preamp

Directionality
Reduce preamp noise! (see NEMO phase 2)

Self noise

Custom Piezo hydrophones (for deep sea)
acoustic sensors with performance well-matched to expected signal

Microscopic model of piezo and coupling
Solved using Finite Element Analysis

Results predictions using equivalent circuits
BAIKAL, ANTARES (Erlangen)
Transducer Amplitude Calibrations

Commercial Hydrophones
- factory calibrated:
  - piston test at 250 Hz, water pool test > 5 kHz (typical)
  - directionality pattern
- sensitivity often changes with pressure
  (about 10 dB less at 3500 m)

High pressure Tests:
- NEMO and NURC (NATO Undersea Research Centre)
  developing a standard procedure for relative calibration under pressure
- Hydrophone response at 0.1 and 300 bar (after several cycles)

Self made hydrophones / glaciophones
- Calibration at low depth
  in large or phono-absorbant pools

NEMO and CNR Corbino (4.5 x 6 x 5.5 m³ pool)
SPATS 78 x 10 x 5 m³ pool
ANTARES (Erlangen) 14 m³ tank, T controlled tank
ANTARES (Valencia) butterfly shaped small tank
Transducers: Glaciophones

The SPATS Module:

- 3 channels
- Piezoceramic
- Low noise preamplifier
- Precalibrated screw

Mass production, typical calibration (in water pool)
Reference hydrophone: Sensortech SQ03: -163.3±0.3 dB re 1V/µPa

sensitivity 2 V/Pa → -114 dB re 1V/µPa
Transducers: Fiber Optic Hydrophones

Optical fibre hydrophones are very interesting:
1) they’re cheap
2) could be used to produce 1 km height vertical arrays

INFN Genova: Fibre optic coiled on an (air) mandrel. Fibre attenuation proportional to Pa.
Good sensitivity up to 5 kHz, low resonance frequency (10 kHz).
Under study: moulding and pressure tests, increase mandrel diameter

INFN Pisa: Herbium doped fibres between Bragg gratings.
Pump at $\lambda_p = 980$ nm $\rightarrow \lambda_L = 1530$ nm laser.
Pressure produce change of cavity length and n. Change of $\lambda_L$ measured with M-Z i.m.

$$\Delta \varphi_{\text{Mach-Zender}} = \frac{2\pi \cdot D}{\lambda^2} \Delta \lambda$$

for SS0 (20 dB re 1 $\mu$Pa/√Hz)
$\Delta \lambda = 10^{-12}$ nm
Requires D = 300 m
$\Delta \varphi = 1$ μrad
Hard but feasible
“Neutrino Pulse” Calibrators

Reliable neutrino signal calibrator: test array capability in reconstructing the \( \nu \) event

ACORNE
Hydrophone excitation
to produce bipolar signal (achieved)

Coherent signal from several hydros
to get pancake shape (under development)

Portable Laser calibrator under study

ANTARES (Valencia)
Parametric Calibrator

Transducers excited with 2 ~1 MHz waves

Non linear effect of ceramic

Bipolar kHz pulse proportional to \( V^2 \)
Signal confined in narrow angles

Simulation
Test Experiments

Ice:

SPATS

Sea:

SAUND
ACORNE
AMADEUS
NEMO-OnDE

Lake:

Baikal
SPATS in ICECUBE Deployment and Operation

Measure ice properties:
attenuation length, wave refraction, noise

3 strings in IceCube holes 72, 78, 47
7 stages per string
stage = 1 transmitter + 1 sensor

surface digitization (200 / 400 kHz)
GPS phased array

String-D
100 m longer
Improved glaciophones
Improved transmitters
New HADES glaciophone
Pinger tests: movable transmitter used in 6 holes (water filled)
AAL to measure sound velocity (Aachen)

blue: SPATS strings
red: pinger holes
SAUND: Study of Acoustic Ultra-high-energy Neutrino Detection

1100 m depth, hydrophones on seabed

SAUND 1: 6 Hydrophones - 7 km²
(signals digitized on shore 100 kHz, 12 bits)
15 days free run

SAUND 2: 56 Hydrophones - 1000 km²
(underwater digitization)
120 days DAQ (target 1 year)
Phased onshore. Sensitivity -186 (+50 gain) dB

Event vertex and energy reconstruction
Test with imploding light bulbs (proven !)

SAUND 2

Ambient noise measured every minute
(input for adaptive matched filter)
Accurate background noise studies
Sea state contribution well separated

Triggered event analysis under study
AMADEUS: ANTARES Modules for Acoustic Detection Under the Sea

3 Acoustics storeys installed on ANTARES Instrumentation Line 07
3 Acoustic storeys installed on ANTARES Line 12 (connected)

IL 07 - Deployment: July 2007  Start data taking: December 2007
Each storey has 6 hydrophones. Spacing between storeys 1 to 300 m
Two storeys of commercial hydros. One storey of self-made hydros
Sampling (underwater) 200 ks/s 16 bits. ANTARES data transmission
Clock system for synchronisation of all acoustic sensors

Measure background noise
Cross check with the ANTARES acoustic positioning system
Test for detection and event reconstruction algorithms
Studies of hybrid detection methods (optic and acoustic)
ACORNE: Acoustic Cosmic Ray Neutrino Experiment

QinetiQ /UK Navy facility at Rona (NW Scotland)
Low depth, noisy environment. Test for trigger and reconstruction

Depth: 230 m
Area: 1.5 km x 200m
8 hydrophones ITC8201 (10 Hz : 65 kHz, -158 dB re 1V / \(\mu\)Pa)
Sampling (onshore): 140 kHz, 16 bits

Hydrophone gain and sensitivity well balanced (proven with noise spectra)
Source reconstruction difficult (hydrophones movements not continuously monitored)

Raw data acquisition 15 days in ‘05, several weeks ‘06

Raw Data Reduction: (230,000 events)
4 triggers: p, dp/dt, \(d^2p/dt^2\), Matched Filter

Data analysis: (3500 events)
35 mPa threshold, 4 fold coincidences

Signal classification:
ringing, sinusoidal, high frequency, bipolar, impulse

Neural network approach in progress
BAIKAL

Infrastructure: BAIKAL NT200+ telescope and surface EAS scintillator array

ITEP antenna / surface EAS array

- Sensitivity -135 dB re V/μPa
- Events sample dominated by surface Background

Thetrahedral antenna / NT200+

- Deployed at 100m
- Noise studies
- Event search

Bipolar pulse on 4 hydrophones

- Angular distribution of bipolar pulses for 2 months data acquisition
NEMO-OnDE: Ocean Noise Detection Experiment

Deployed at the NEMO Test Site 2000 m depth, 25 km offshore Catania. Next deployment end of 2008, in the framework of ESONET-LIDO demo mission. There is a Deep Sea Test Site facility available for R&D!

Thetrahedral antenna (1m size):
4 Reson TC4042 hydrophones (special production for 2500 m depth).
Low cost professional audio electronics (96 kHz, 24 bit sampling, $\Delta\Sigma$)
Hydrophones synchronised and phased.
On-line monitoring and recording on shore. Recording 5’ every hour
Data taking from Jan. 2005 to Nov. 2006 (NEMO Phase 1 deployed).
Sea Noise measurement and modelling (presently under study)
Bioacoustics: study of sperm whales population in the East Med Sea
Test of triggers and reconstruction (limited size: 1m ) algorithms under test (using also ACORNE software tools)

Sperm whale click

Eastern Sicilian Coast

Catania Site

Capo Passero Site

4 hydrophones

electronics housing

Giorgio Riccobene

LNS
NEMO Phase II – Acoustic Positioning and Acoustic Physics

NEMO Phase II: Installation and operation of a “full scale” tower in Capo Passero
16 floors, 64 Optical Modules, 750 m total height

Same electronics and DAQ and DAT as NEMO Phase I:
OM data synchronised and phased (about 1 ns resolution)

34 hydrophones for Acoustic Positioning … And for Acoustic Physics / Biology

→ Reduce costs and improve reliability of the tower acoustic positioning system
→ 750 m long antenna for feasibility studies on acoustic detection
→ Optical and acoustic data in the same data stream with the same time
  All signals are phased!
  A viable solution for KM3Net (?)

Hydrophones (SMID-NURC) 30 (-207 dB) + 4 (-201 dB) Tested for 3500 m
Preamp (SMID-NURC) 32 dB gain, 0.8 nV/√Hz input noise
ADC-board 24 bits, 192 kHz sampling, 3 dB gain
FCM Optical Transmission to shore + GPS time stamp
NEMO Phase II – “Acoustic” Electronics Chain

“All data to shore” philosophy
data payload: 2 Hydros = 1 OM, fully sustainable

Hydros + preamps

ADC

Floor Control Module
Adds GPS Time
Send data to shore

Acoustic Data Server

Acoustic Physics / Biology

On-Shore Floor Control Module
Data Parsing

Acoustic Positioning

Hydros

OMs

Acoustically and electrically noisy environment

Dynamic range > 90 dB [0 : 96 kHz] (to be improved)
Excellent for acoustic positioning signals
Equivalent self noise
(-207 dB hydro) 35 dB re 1 µPa/√Hz [1:48 kHz]
(-201 dB hydro) 29 dB re 1 µPa/√Hz [1:48 kHz]

Present professional audio Σ-Δ ADC are noisy at f > 48 kHz

NEMO Phase II “Acou-Board”

Giorgio Riccobene LNS
Summary

Simulations
Several reliable codes available for neutrino interactions and EAS in water / ice, and for acoustic wave formation

Medium properties (acoustic wave propagation, noise)
Water: well known, a deep sea site for a large installation would require further studies
Ice: requires better investigation
Other: Salt, Permafrost (R. Nahnhauer) interesting to investigate

Event trigger and reconstruction
Available, require further improvements

Technological R&D:
Hydrophones (ceramics) available, present costs about 1000€ (could be reduced)
Tune custom hydrophones for neutrino pulse range? Improve sensitivity for high depth
Amplitude calibration required for high pressure (and low temperature in ice)
“Synthetic neutrino pulse” emitters soon available
Dedicated DAQ or “cheap” professional audio electronics (with improvements)?

Test Sites:
Opportunity to test technology / software

Acoustic detection using the km$^3$ Cherenkov telescope infrastructure:
Acoustic positioning system is required in water, use it also for acoustic physics
Performances could be competitive with a small effort… KM3Net? …
Personal Comments

There are lots of improvements in the UHE neutrino acoustic detection field.
Small groups applying for a common EU FP7 JRA on Acoustics (thanks to L. Thompson).

ARENA Conferences were and are a great opportunity for discussion.

Workshop on acoustic detection 2003
ARENA 2005
ARENA 2006
ARENA 2008

Stanford
Zeuthen
Newcastle
Roma, Next June 25-28
Final Note

Dolphins use sound!

They’re the second most evolved species on Planet Earth

… Mankind is only the third!