Acoustic detection of UHE neutrinos: status and and perspective

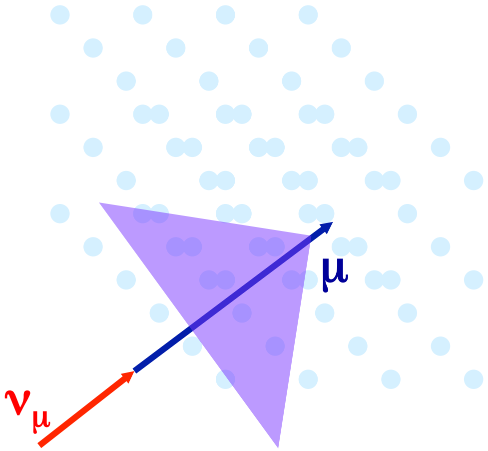
Outlook

- Neutrino detection techniques
- Thermo-acoustic mechanism
- Event simulation
- Medium properties
- Transducers
- Test experiments
- Conclusions

Large Area Detectors for HE neutrinos

1 TeV — 100 PeV — 1000 ZeV

Optical Detection (ICECUBE-KM3NeT)



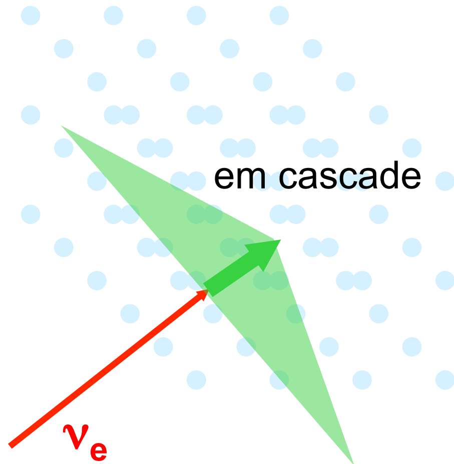
Medium: Seawater, Polar Ice

ν_μ (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)



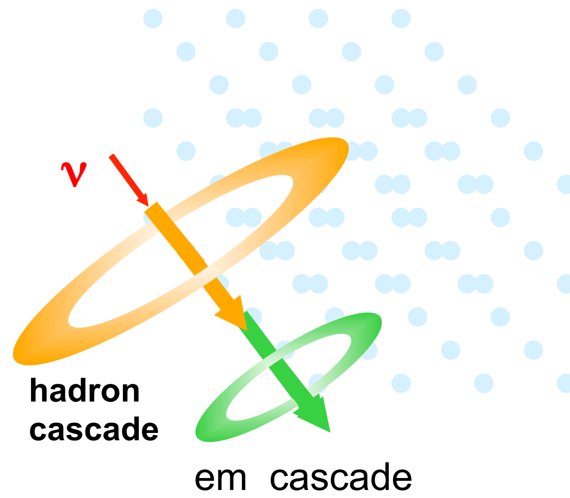
Medium: Salt domes, Polar Ice

ν (cascades)

Carrier: Cherenkov Radio
Attenuation length: 1 km

Sensors: Antennas
Instrumented Volume: >1 km^3

Acoustic Detection (Prototypes)



Medium: Seawater, Polar Ice, Salt Domes

ν (cascades)

Carrier: Sound waves (tens kHz)
Attenuation length: ~ 10 km

Hydro(glacio)-phones
Instrumented Volume: >100 km^3

Basics of thermo-acoustics mechanism

A pressure wave is generated by the quasi- instantaneous heating of a macroscopic water volume in which a high-energy shower has developed.

Istantaneous deposition of heat through ionization

$$t_{deposition} \approx D / c \approx 10^{-7} : 10^{-8}\ sec$$

Thermo-acoustic process:
increase of temperature (specific heat capacity C_p), expansion (expansion coeff β)

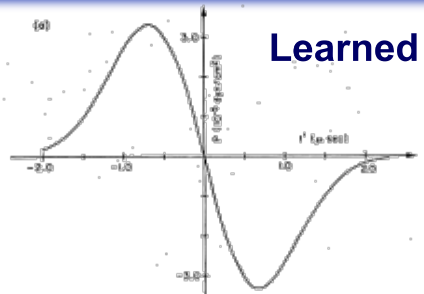
$$t_{expansion} \approx 10^{-5}\ sec \gg t_{deposition}$$

$$\nabla^2 \mathbf{p} - \frac{1}{\mathbf{c_s}^2}\ddot{\mathbf{p}} = -\frac{\beta}{\mathbf{c_p}} \cdot \frac{\partial \varepsilon(\mathbf{r},\mathbf{t})}{\partial \mathbf{t}}$$

For a point like source (micropulse):

$$\mathbf{p}(\mathbf{r},\mathbf{t}) \propto \frac{\mathbf{E}_0\beta}{4\pi\mathbf{c_p}} \frac{\partial}{\partial \mathbf{t}} \frac{\delta\left(\mathbf{t} - \frac{\mathbf{r}}{\mathbf{c_s}}\right)}{\mathbf{r}}$$

Bipolar pulse
spherical expansion



Learned

For a shower heating a volume of matter (neglecting absorption and reflaction):

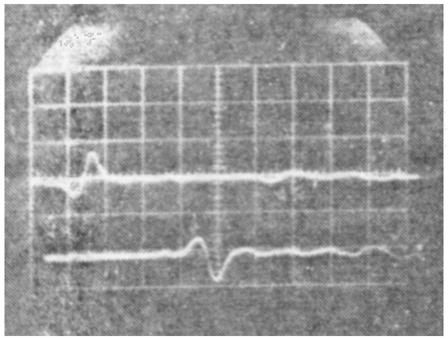
$$\mathbf{p}(\mathbf{r},\mathbf{t}) \propto \frac{\beta}{4\pi\mathbf{c_p}} \frac{\partial}{\partial \mathbf{t}} \int \frac{1}{\mathbf{r}} \varepsilon\ \mathbf{dV}$$

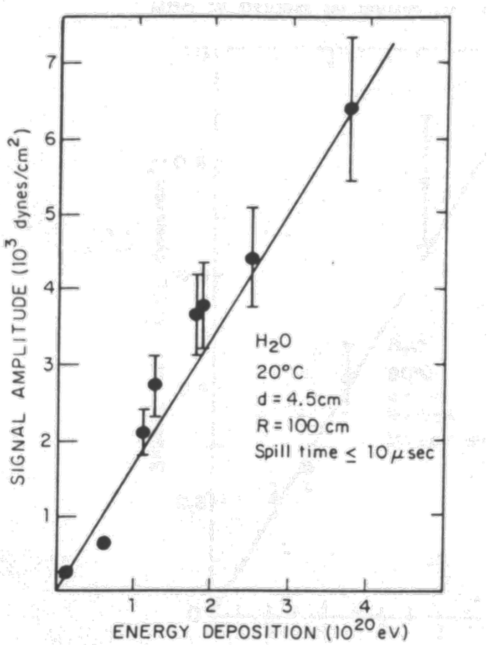
Sum of pointlike sources:
wavefront and signal shape depend on the energy density distribution

Experimental proof of the thermo-acoustic mechanism

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)

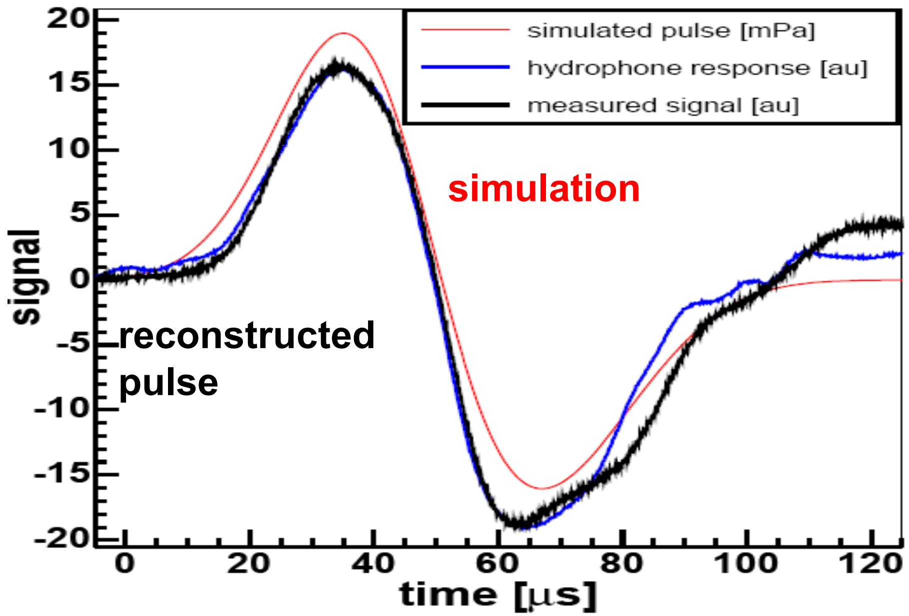




Recent measurements (2000's)

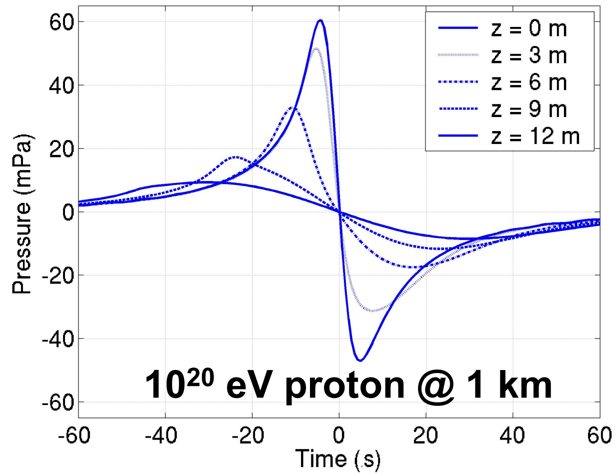
ITEP Synchrotron: 100, 200 MeV p
E= $10^{15} - 10^{20}$ eV
Measured pulse amplitude increses linearly with E

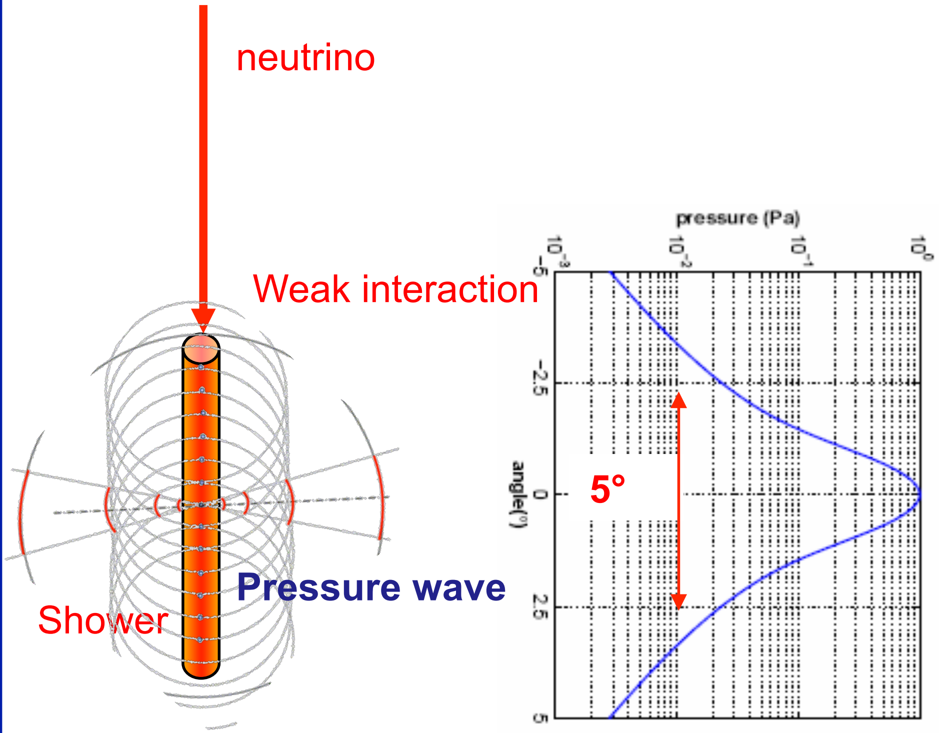
Erlangen Laser Nd-YaG
E= $10^{17} - 10^{19}$ eV
Dependence on C_p confirmed

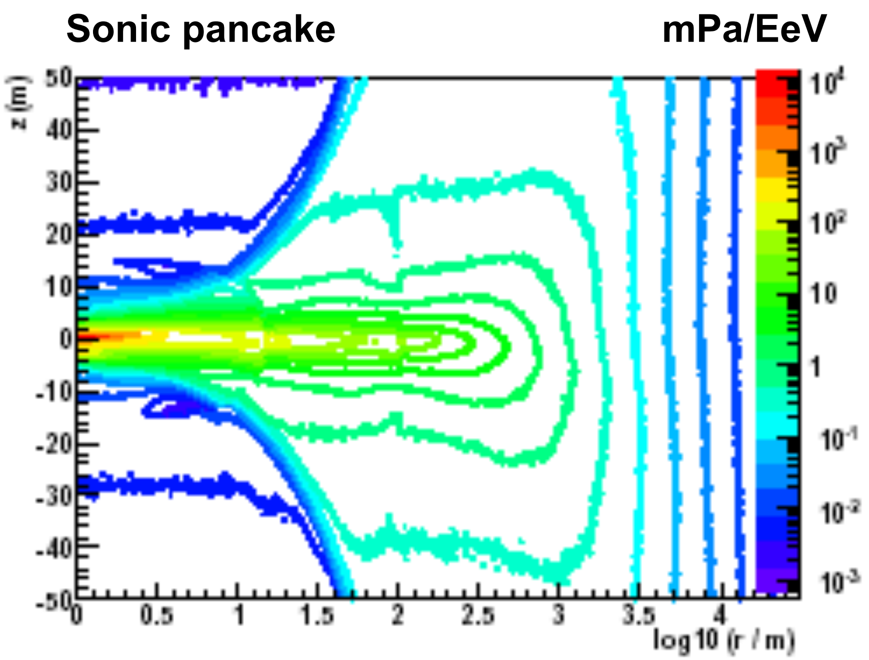


Based on the Learned paper 1979

The simultaneous sound production along the shower results in a coherent emission in the plane perpendicular to the shower axis. The "pancake" is very collimated and the pulse changes as a function of angle both in amplitude and shape.





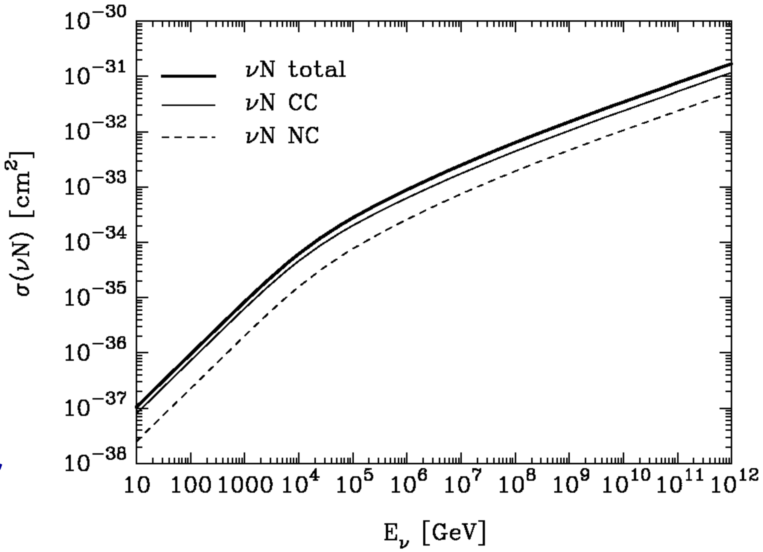


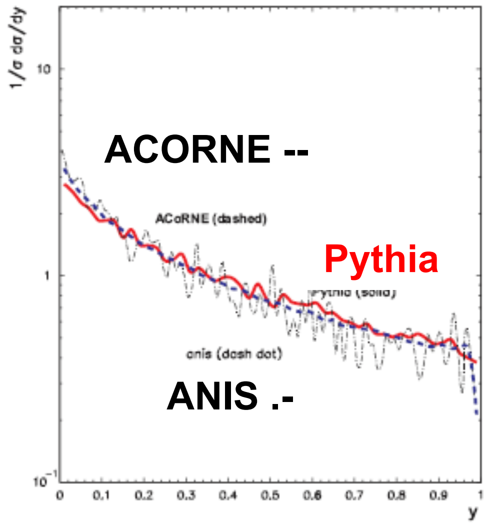
Simulations of neutrino interaction and shower propagation

Neutrino Interaction

ANTARES(Erlangen,Marseilles)
SAUND
Ghandi et al.

ACORNE
ANIS (from Amanda)
HERWIG+CORSIKA
neutrino shower simulator



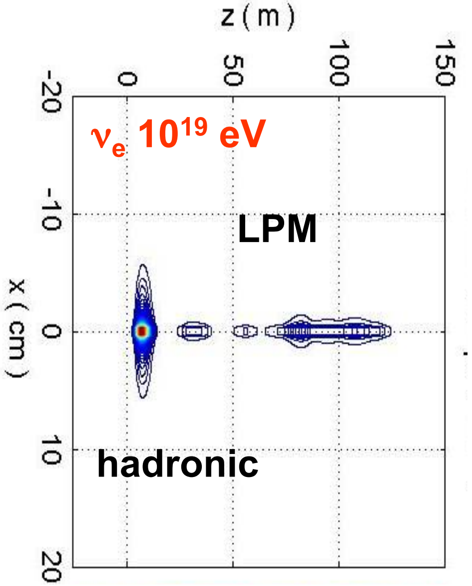


Shower development

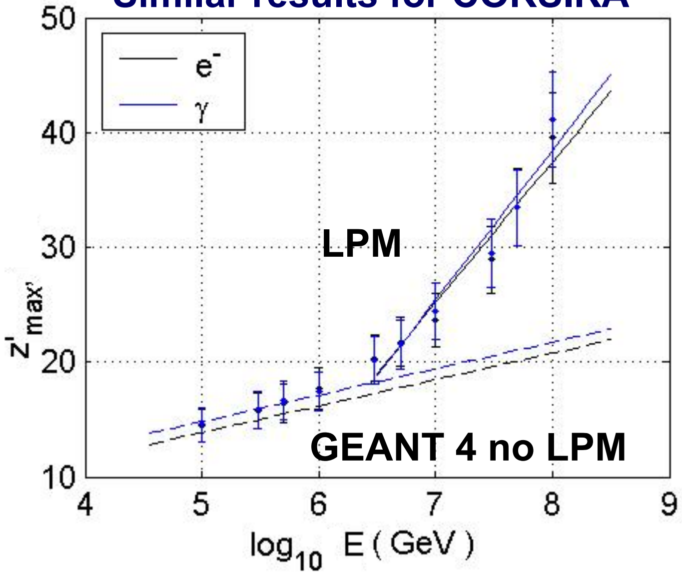
Zheleznyk and Dedenko
(e.m. shower including LPM)

SAUND
hadronic
Alvarez Muniz-Zas

ANTARES (Marseilles)
Hadronic + e.m.
GEANT 4 +LPM



Similar results for CORSIKA



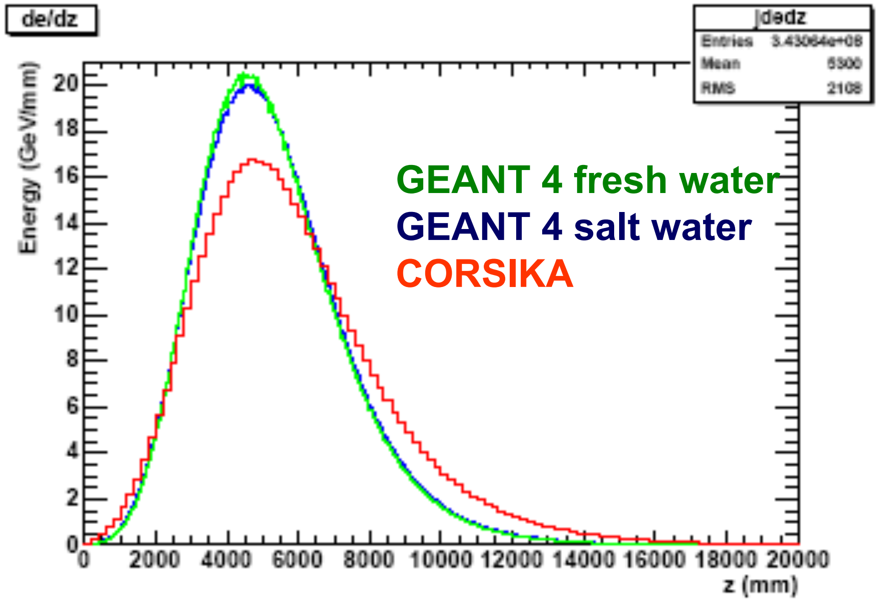
Simulations of neutrino interaction and shower propagation

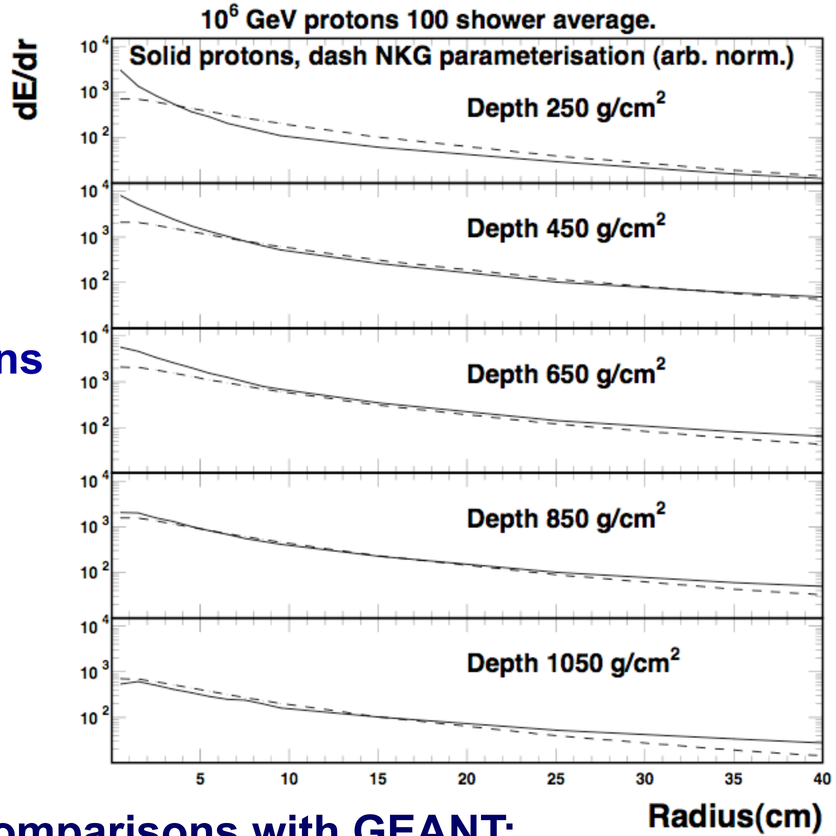
Shower development

ACORNE:

CORSIKA modified for water

transverse and longitudial energy deposits have been parameterized for fast simulations





Astropart Phys V28 3 (2007) 366

Comparisons with GEANT:

- ~ 10% lower at peak
- Showers broader

Comparison with NKG:

- less energy at smaller radii
- low frequency contribution enhanced)

Study of the Medium Acoustic Properties : Water

Complex but well characterized by several military studies

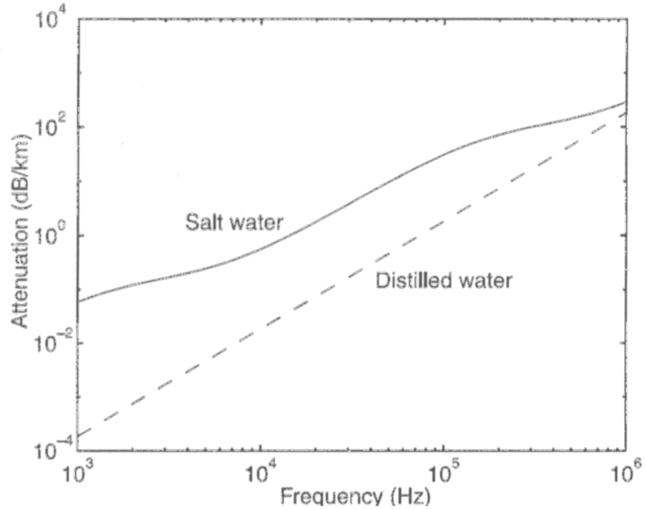
Absorption is mainly caused by chemical relaxation:

$B(OH)_3$ 50 Hz - 5 kHz

$MgSO_4$ 5 kHz – 500 kHz

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

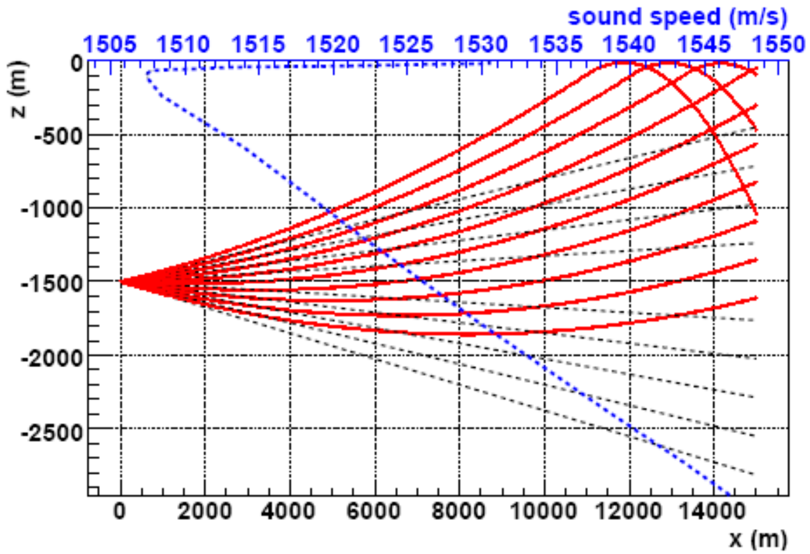
$L_a \approx 10$ km (at 10 kHz)



Sound velocity in water changes as a function of depth, tempeature and salinity. Near the surface T and S contributions dominate while at large depth only the pressure contribution vary; so the sound velocity increases linearly with depth.

→ refraction $\frac{\Delta c_s}{\Delta z} = 1.65$ cm/s/m

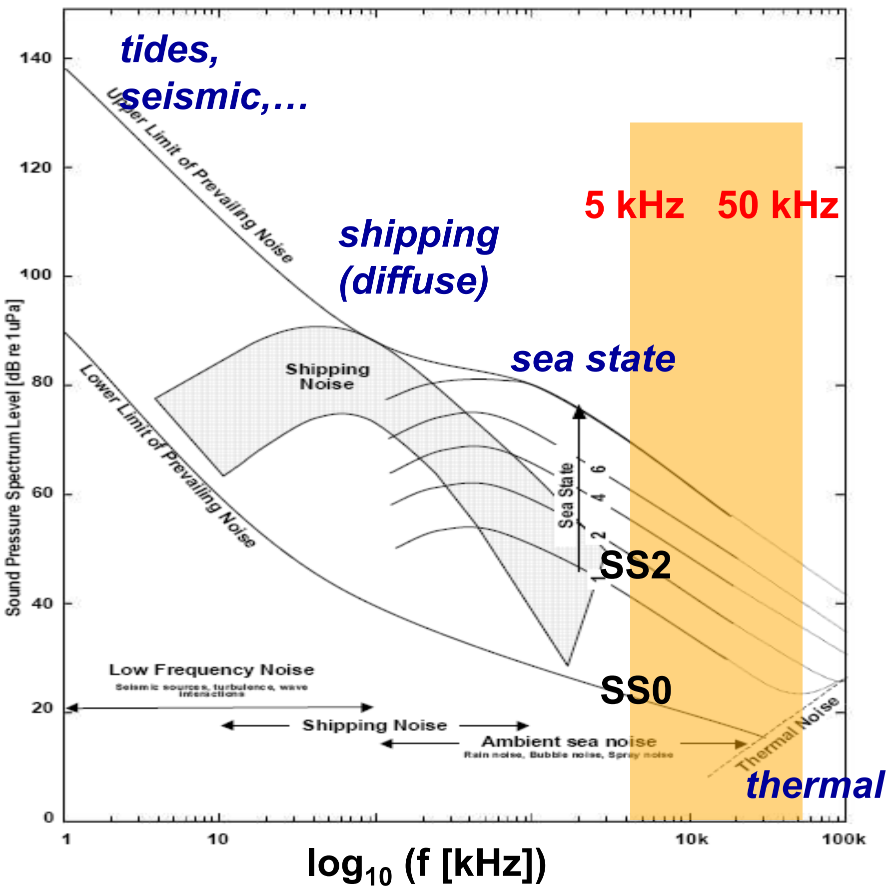
pancake shape modification

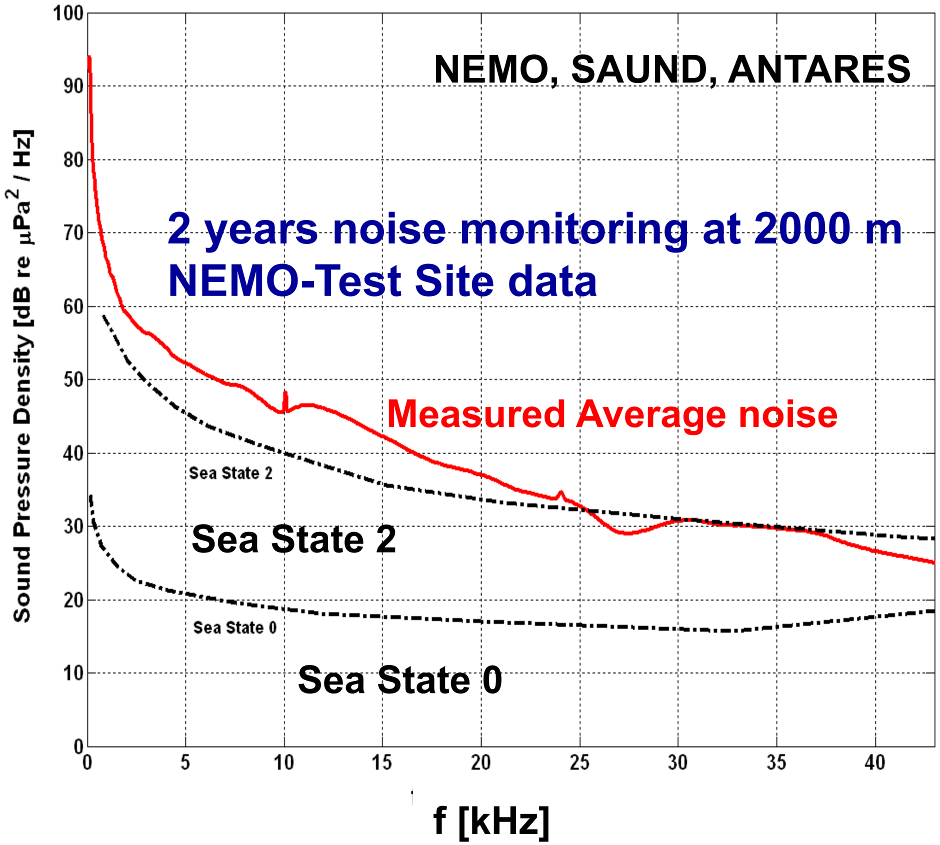


Acoustic Noise in Water

Diffuse noise: Seismic, surface waves (wind), rain, thermal noise

Impulsive noise: Cetaceans, man made shipping and instrumentation





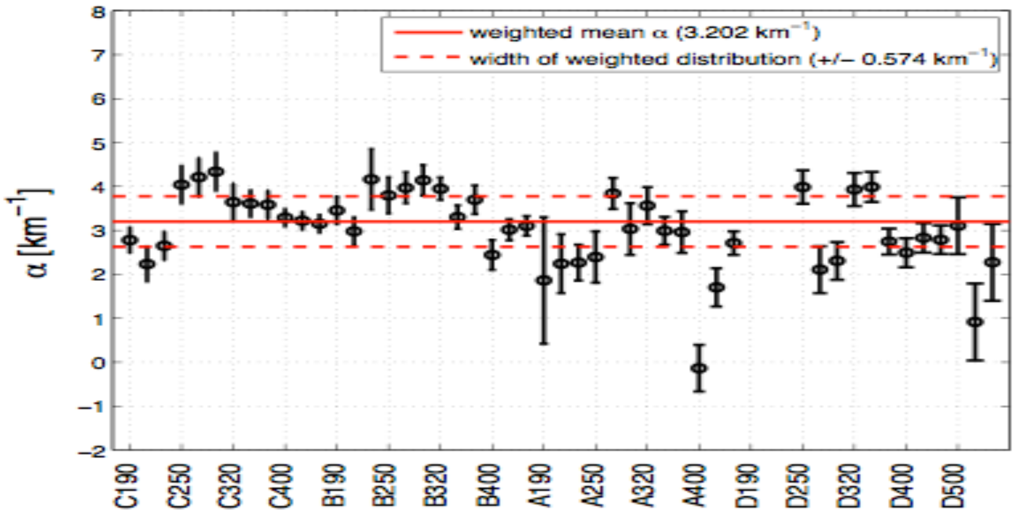
Knudsen's Formula

$$P(f_{Hz}, SS) = 94.5 - 10\,log\,f^{5/3} + 30\,log(SS+1)$$

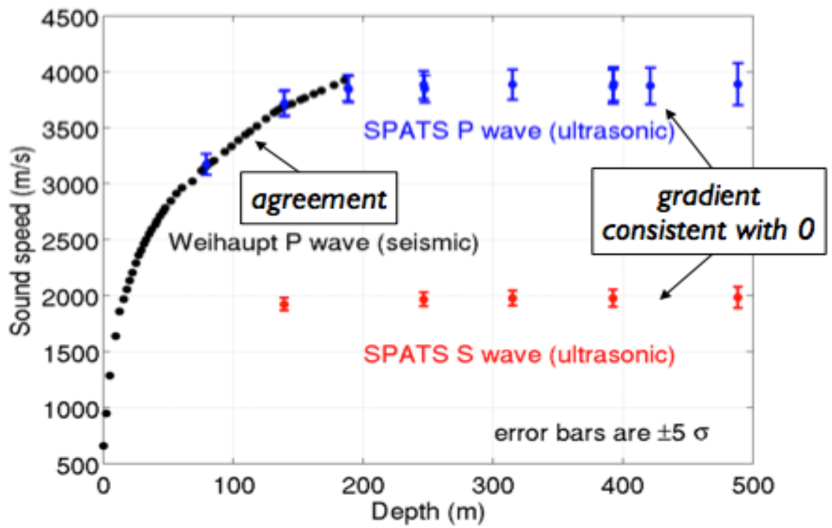
Study of the Medium Acoustic Properties : Polar Ice

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

scattering	absorption	speed of sound
Rayleigh scattering at crystal boundaries →crystal size →frequency $\lambda_s \sim a^3 \times f^4$	molecular reorientation → energy loss in relaxation temperature dependent crystal size dependent	weak temperature dependence strong depth dependence only near the surface. Signal refraction is important near surface. pressure waves: v_s = 3900 m/s shear waves: v_s = 2000 m/s



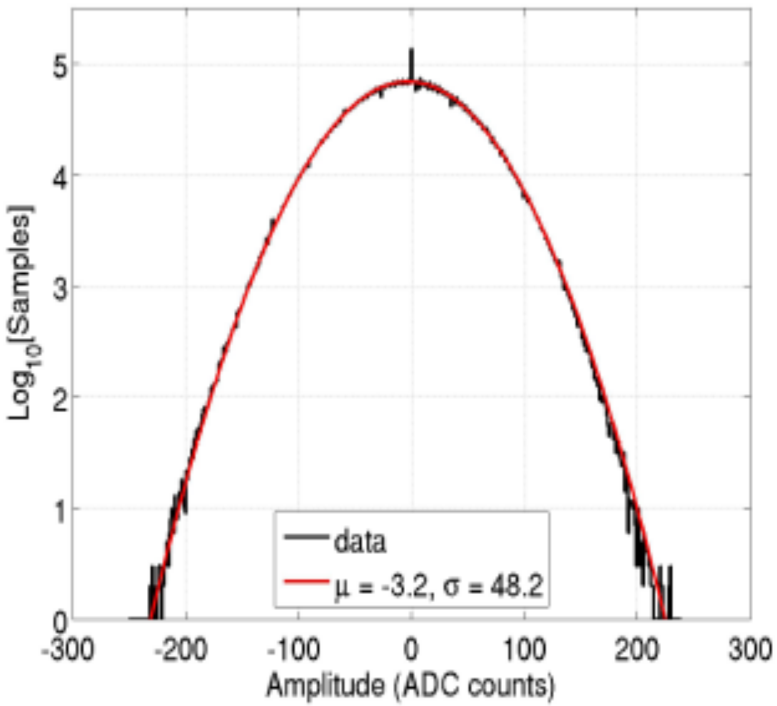
Attenuation length is about 300m compared to expectation of kms. Further data analysis is going on.



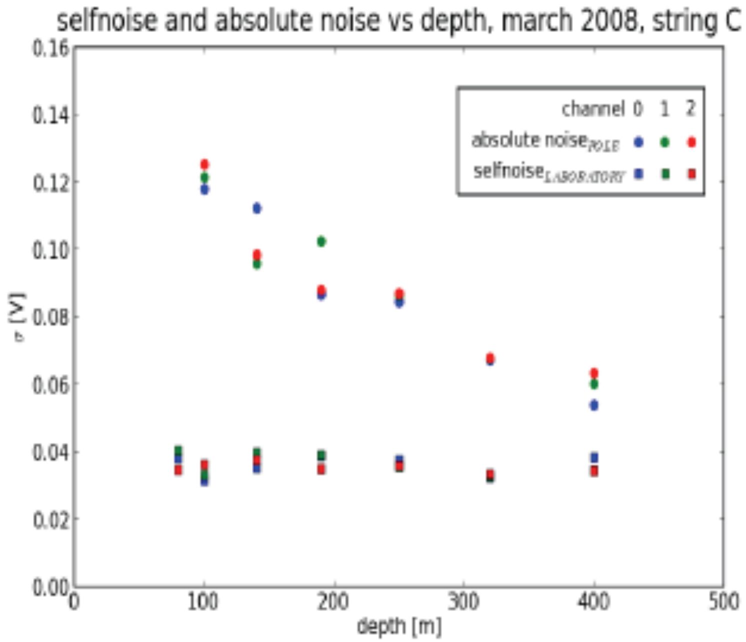
Acoustic Noise in Ice

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

Transducers: Commercial 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.

Hydrophone + preamplifier moulded in deep sea cable 7.5 m length

Commercial Hydrophones

factory calibrated:

→ piston test at 250 Hz, water pool test > 5 kHz (typical)

→ directionality pattern

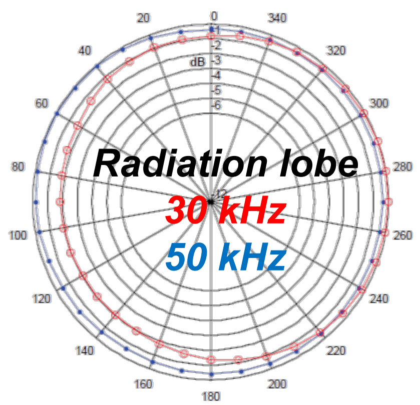
sensitivity often changes with pressure (about 10 dB less at 3500 m)

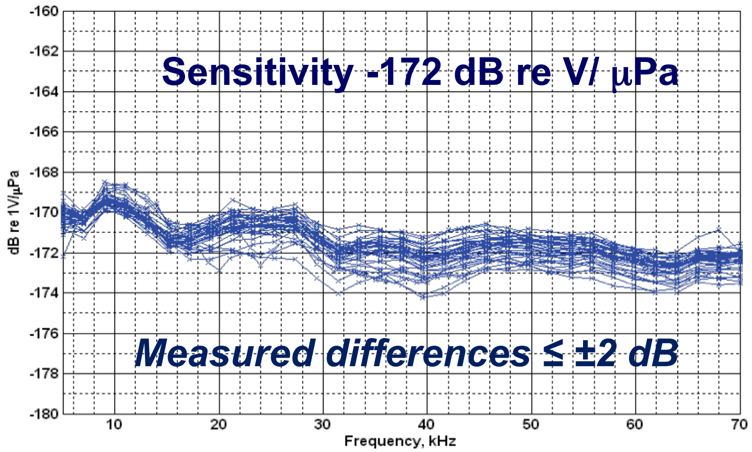
High pressure Tests :

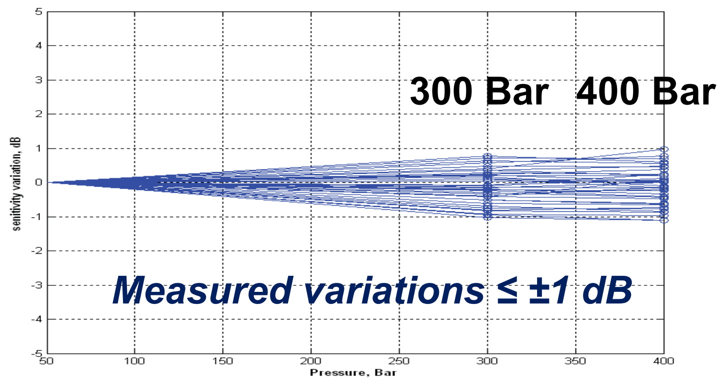
NEMO and NURC (NATO Undersea Research Centre)

developing a standard procedure for relative calibration under pressure

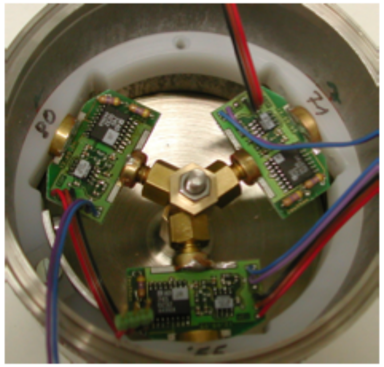
Hydrophone response at 0.1 and 300 bar (after several cycles)





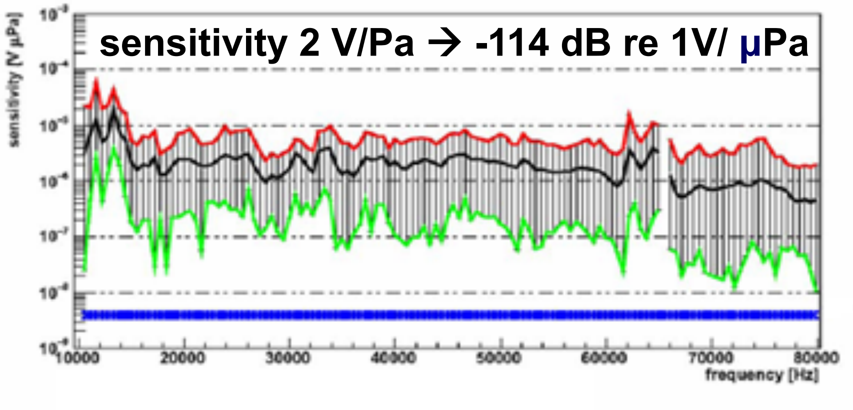


Transducers: Custom Sensors



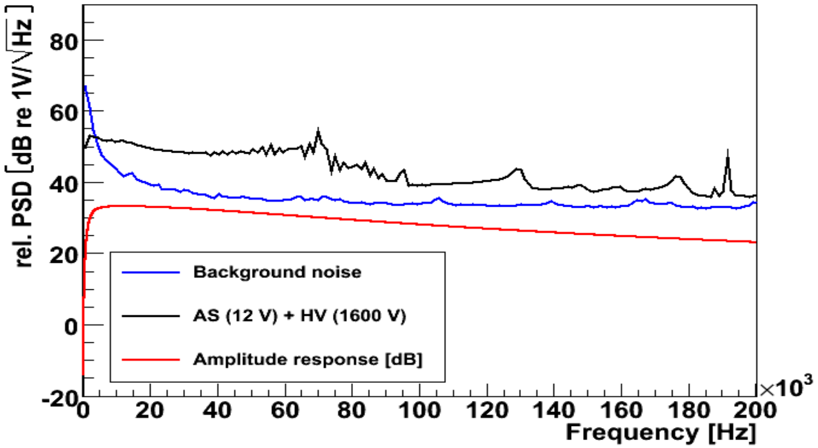
The SPATS Module:

3 channels
- **Piezoceramic**
- **Low noise preamplifie**
- **Precalibrated screw**



The AMADEUS Module:

3 channels
- **Piezoceramic**
- **Acoustic sensor glued**
- **Built in preamplifier**



Microscopic model of piezo and coupling
Solved using Finite Element Analysis

Results predictions using equivalent circuits

Needs investigation regarding the mechanical matching and the acoustic impedence at the interfaces

"Neutrino Pulse" Calibrators

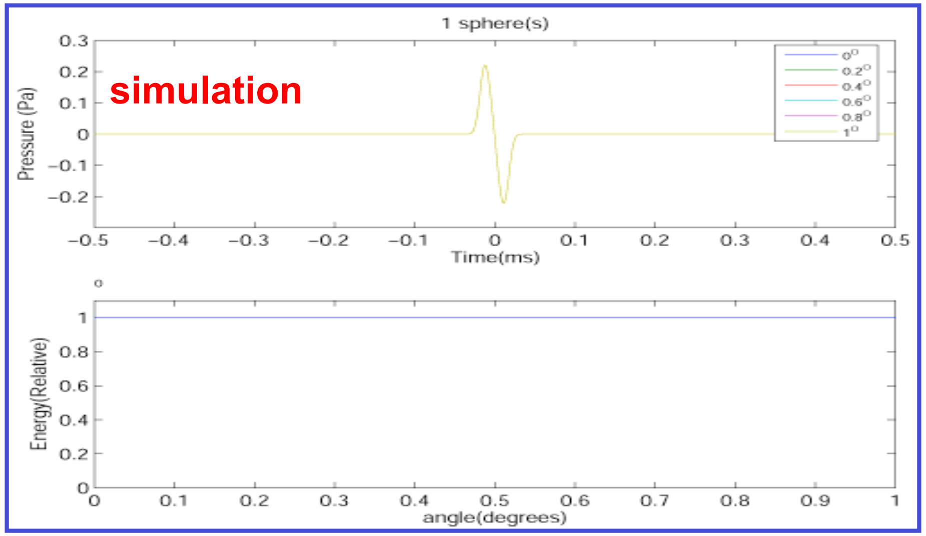
Reliable neutrino signal calibrator: test array capability in reconstructing the ν event

ACORNE

Hydrophone excitation to produce bipolar signal (achieved)

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

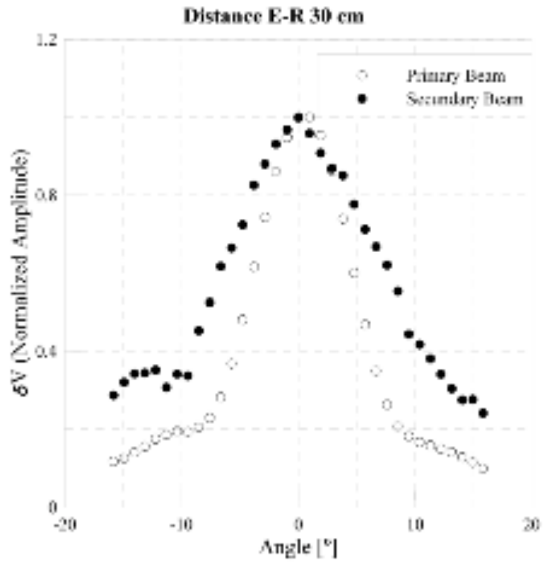
Portable Laser calibrator under study



ANTARES (Valencia)

Parametric Calibrator:
Transducers excited with 2 ~1 MHz waves near the resonance of the emitter. It's based on a non linear effect of the ceramic.

Bipolar kHz pulse proportional to V^2
Signal confined in narrow angles. First results are promising, further work is going on.



SPATS in ICECUBE Deployment and Operation

Measure ice properties :
attenuation length, wave refraction, noise

4 strings

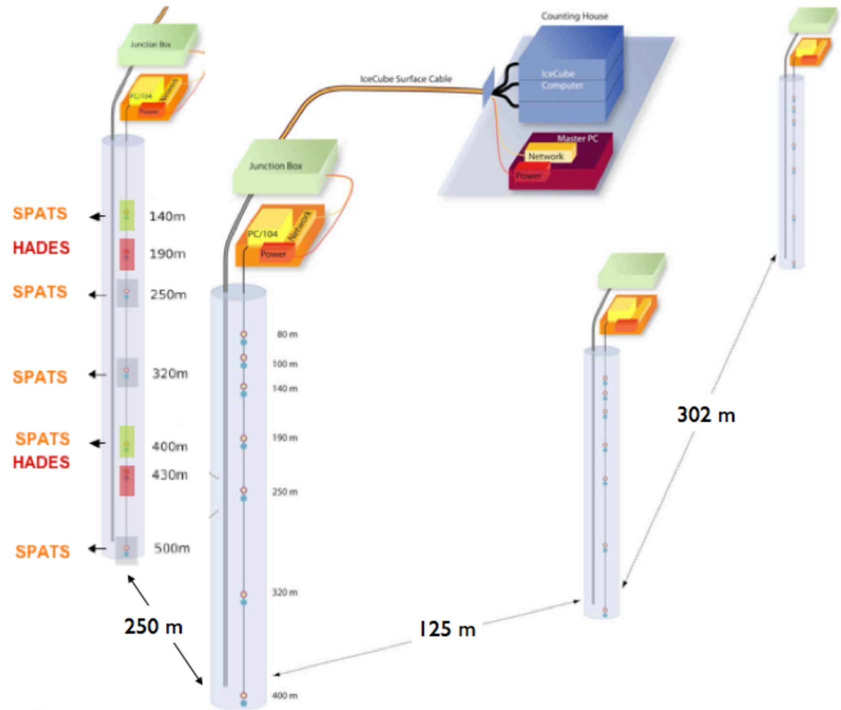
7 stages per string

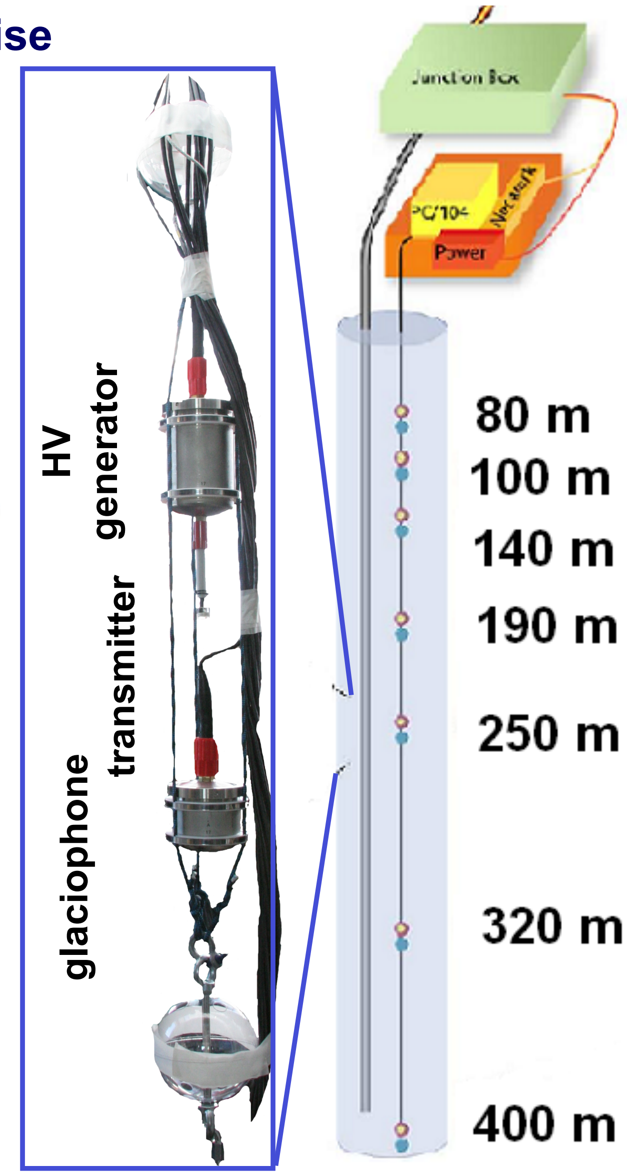
stage = 1 transmitter + 1 sensor

Instrumented depth 80m – 500m

surface digitization (200 / 400 kHz)

GPS phased array

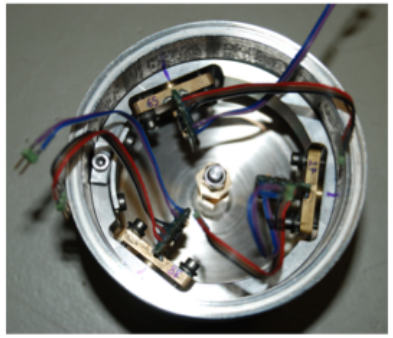




String-D
100 m longer

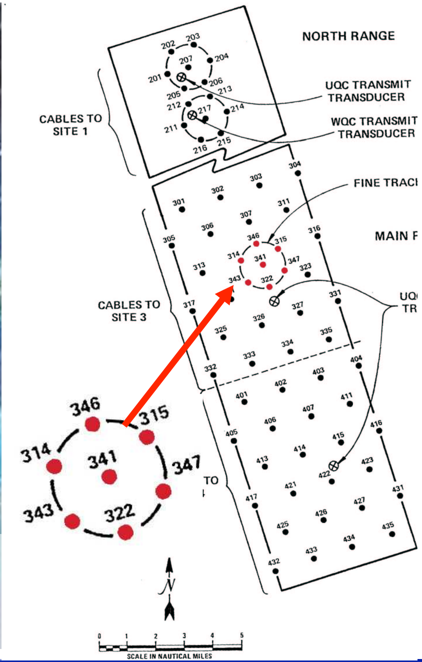
Improved transmitters

Improved Glaciophones: mechanical decoupling of sensor channels.



New HADES glaciophone: Sensor design with sensors outside the steel housing

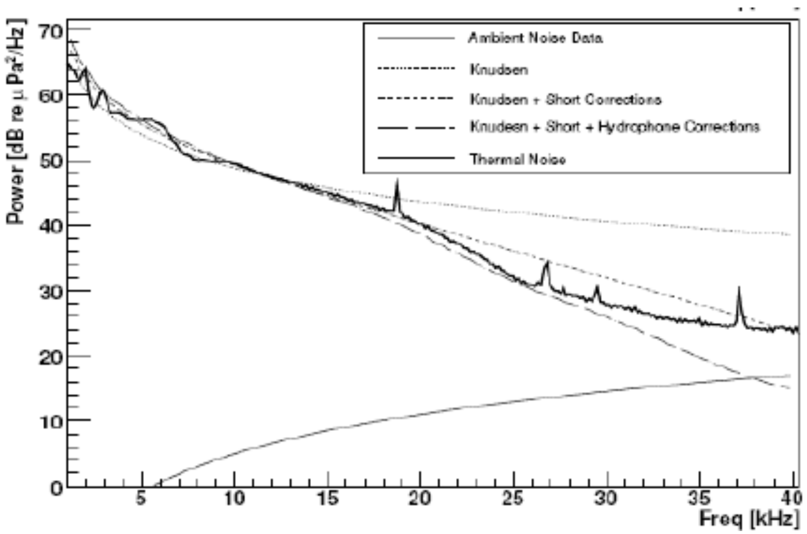
SAUND: Study of Acoustic Ultra-high-energy Neutrino Detection



1100 m depth, hydrophones on seabed

SAUND 1: 6 Hydrophones - 7 km^2
(signals digitized on shore 100 kHz, 12 bits)
15 days free run
SAUND 2: 56 Hydrophones - 1000 km^2
(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

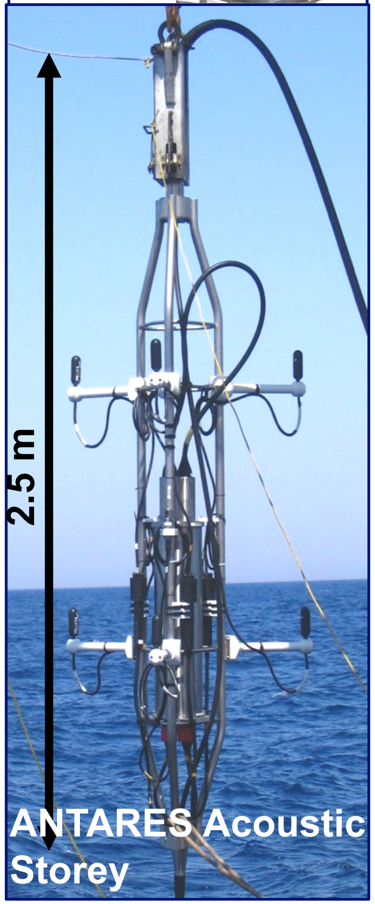


SAUND 2

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

Triggered event analysis under study

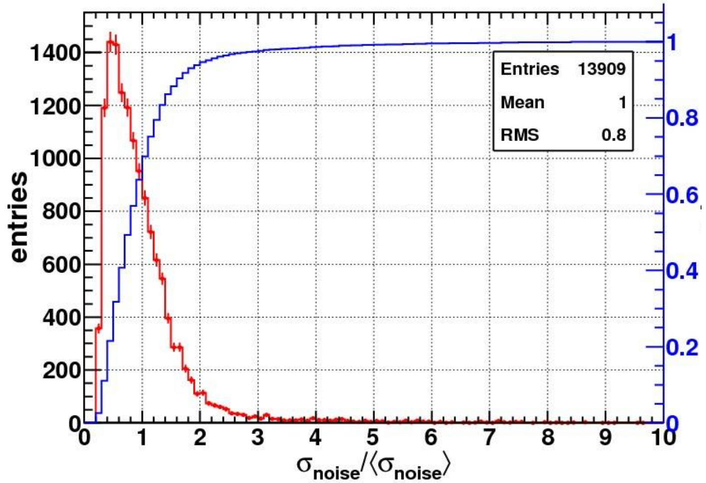
AMADEUS: ANTARES Modules for Acoustic Detection Under the Sea

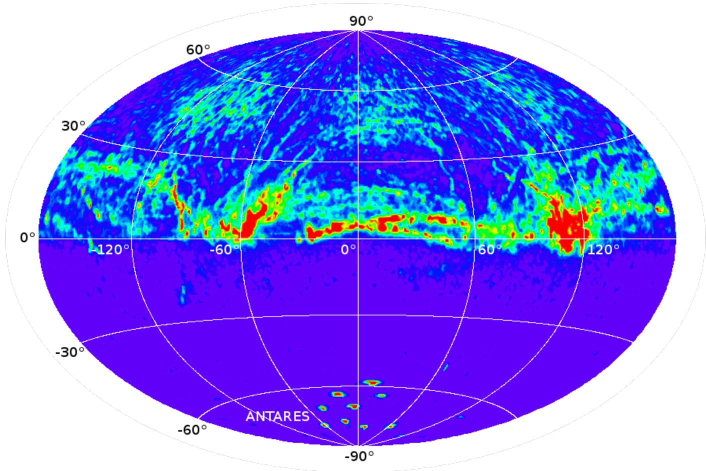


3 Acoustics storeys installed on ANTARES Instrumentation Line 07
3 Acoustic storeys installed on ANTARES Line 12 (connected)

Each storey has 6 hydrophones.Spacing between storeys 15 to 300 m
One storey of self-made hydros. Typical sensitivity: -145 dB re 1V/μPa
Sampling (underwater) 200 ks/s 16 bits. ANTARES data transmission
Clock system for synchronisation of all acoustic sensors

Long term background investigation and its correlation with ambient.
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

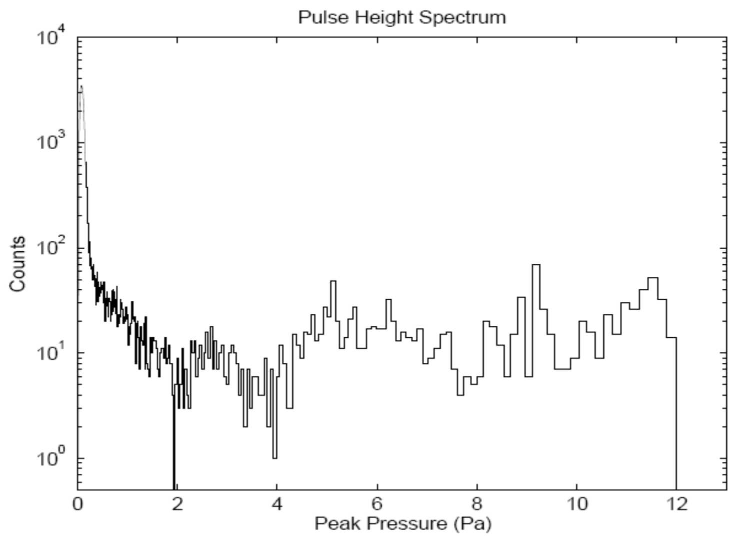
Depth: 230 m Area: 1.5 km x 200m
8 hydrophones ITC8201 (10 Hz : 65 kHz, -158 dB re 1V / μPa)
Sampling (onshore): 140 kHz, 16 bits

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

Data acquistion: 245 total day of unfiltered data

Raw Data Reduction: p, dp/dt, d^2p/dt^2, Matched Filter

Single hydrophome analysis:
- Has to be a single – not part of a train
- Shorter that about 0.35ms
- No significant change in background before and after the pulse
- |Skewness| <0.5
- Kurtosis<5



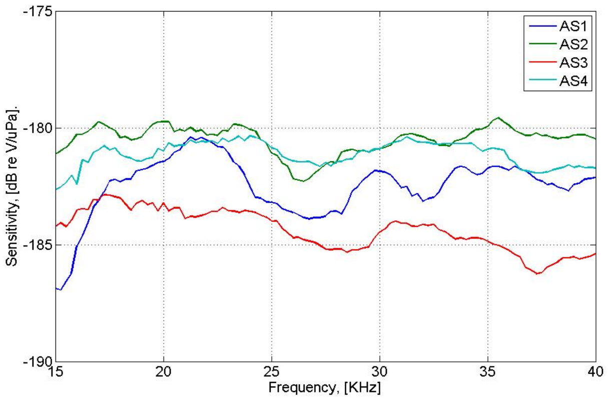
BAILKAL

Infrastructure: BAIKAL NT200+ telescope and surface EAS scintillator array

Single Hydrophone

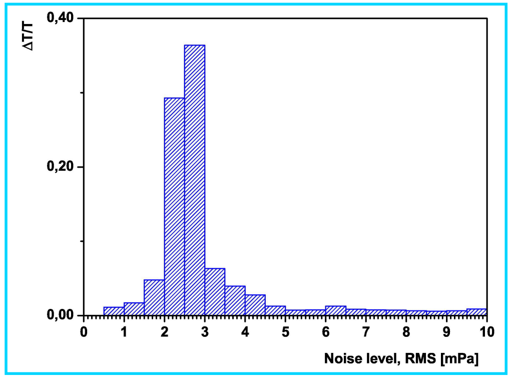
Sensitivity -185 dB re V/ μPa

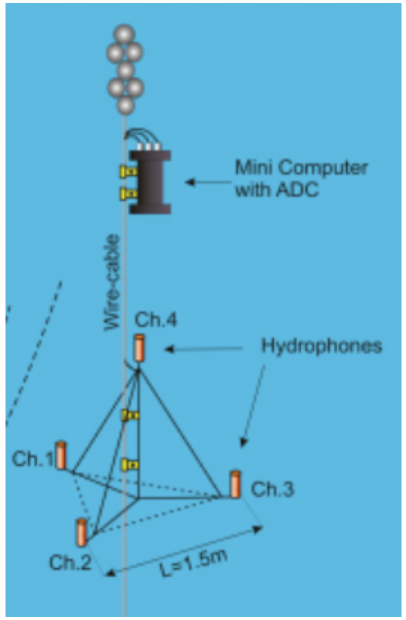
Operating depth up to 1000m



Thetrahedral antenna / NT200+
4 ch. Sampled at 192kHz 16bit.

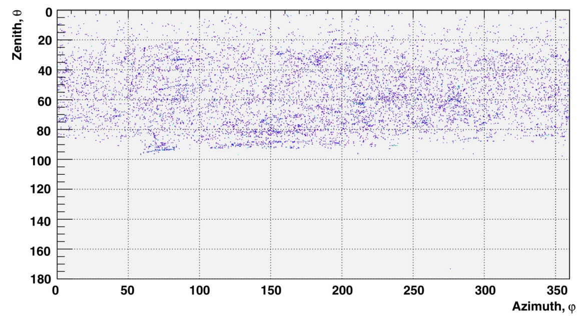
Deployed at 150m
Noise studies
Event search



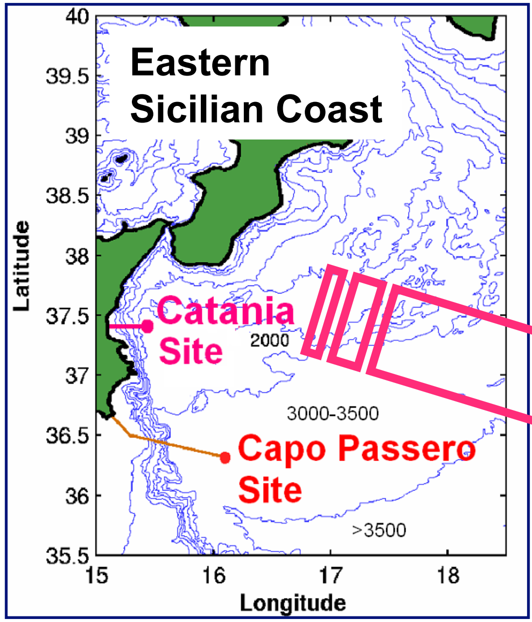


Bipolar pulse on 4 hydrophones

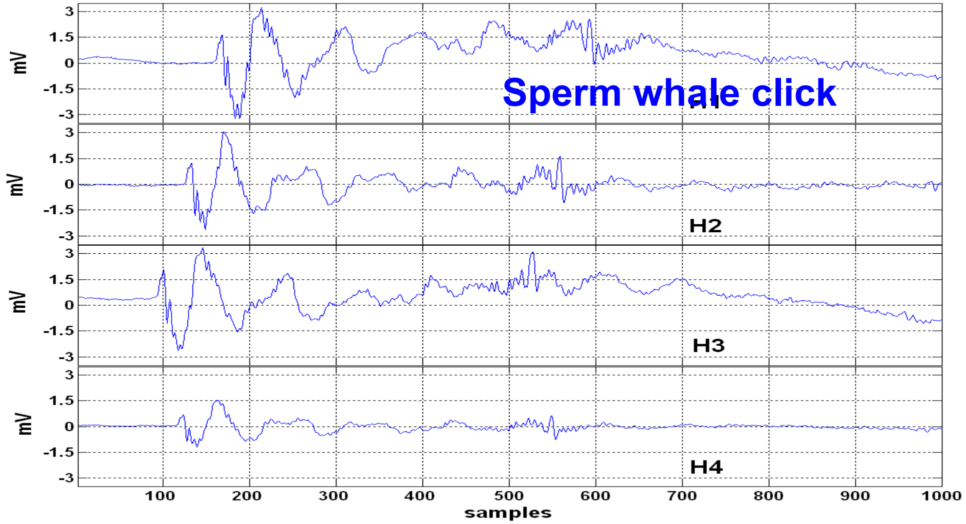
Angular distribution of bipolar pulses (April-May 2009)

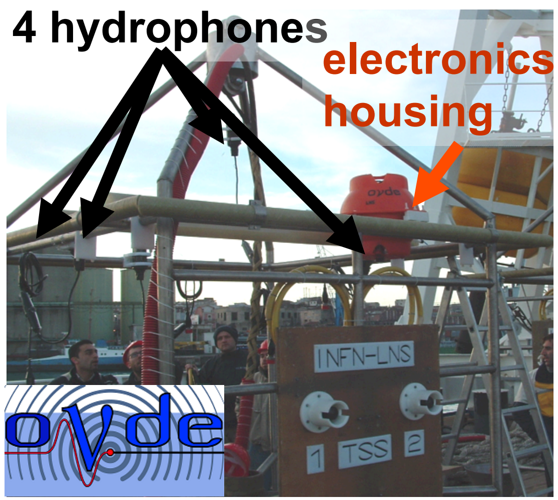


NEMO-OnDE: Ocean Noise Detection Experiment



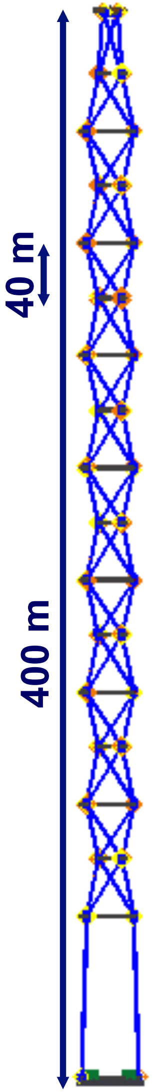
Deployed at the NEMO Test Site 2000 m depth, 25 km offshore Catania.
Next deployment in the framework of ESONET-LIDO demo mission.
There is a Deep Sea Test Site facility available for R&D





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)

NEMO Phase II – Acoustic Positioning and Acoustic Physics



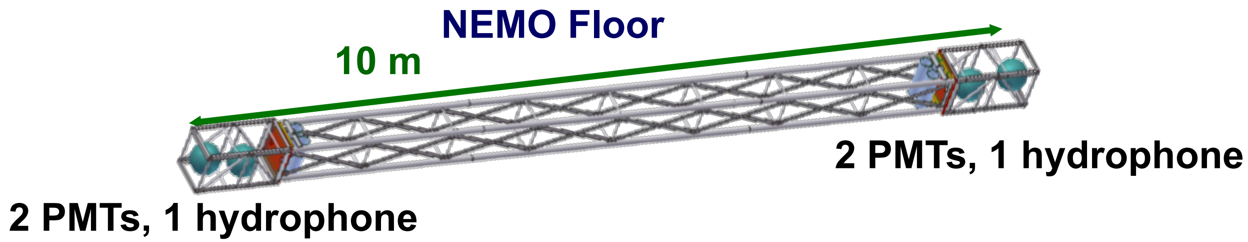
NEMO Tower

NEMO Phase II: Installation and operation of a tower in Capo Passero
8 floors, 32 Optical Modules, 400 m total height. Deployment 2011

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

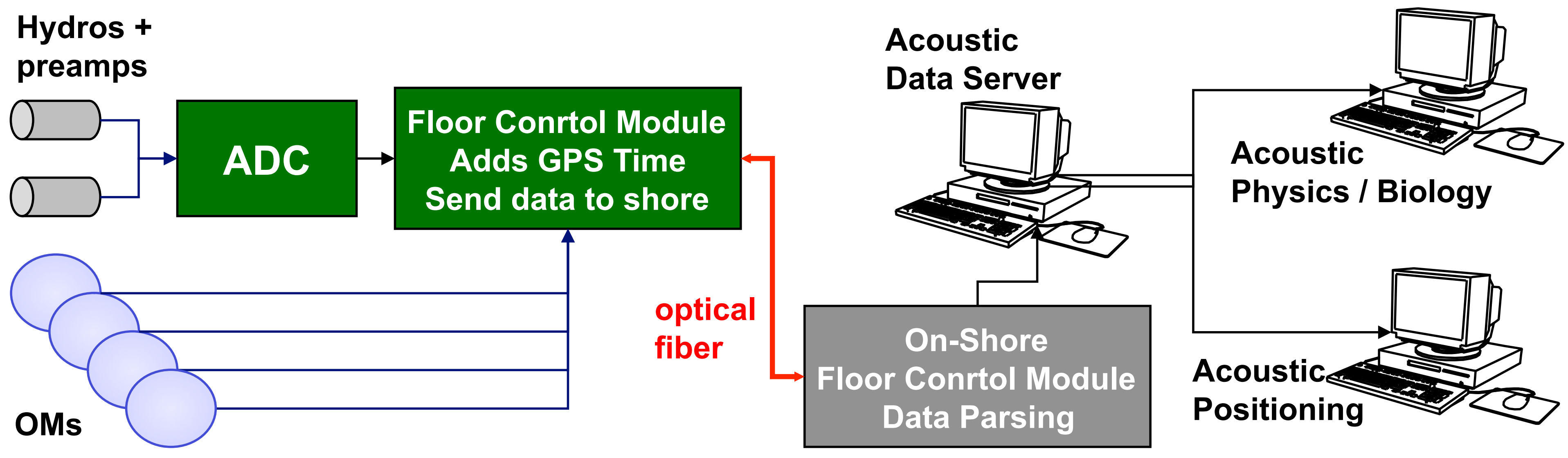
20 hydrophones for Acoustic Positioning …And for Acoustic Physics / Biology

→ Reduce costs and improve reliability of the tower acoustic positioning system
→ 400m long antenna for feasibility studies on acoustic detection
→ New pressure calibrated hydrophones (in collaboration with NATO)
→ New front-end electronics
→ Optical and acoustic data in the same data stream with the same time
  All signals are synchronous and phased
  It could be a compliant solution for KM3Net

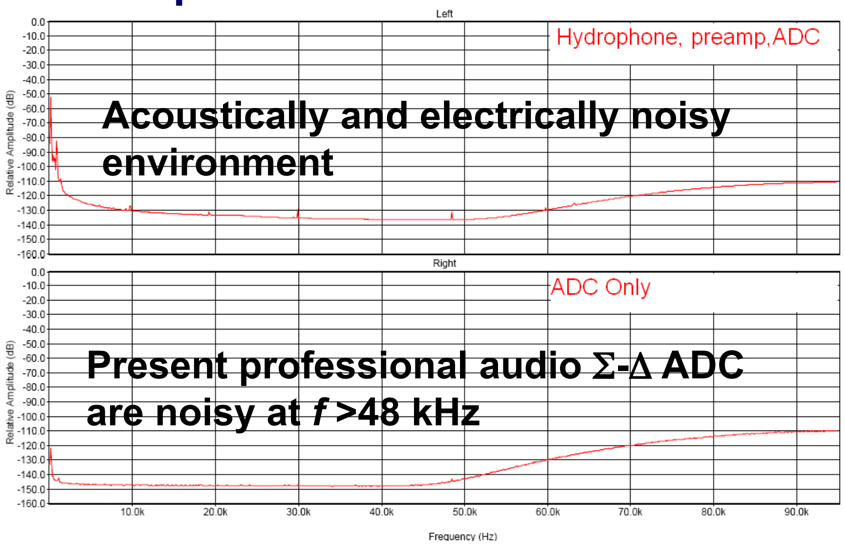


NEMO Phase II – "Acoustic" Electronics Chain

"All data to shore" philosophy | **data payload: 2 Hydros = 1 OM, fully sustainable**



Complete DAQ chain tested



Dynamic range > 90 dB [0 : 96 kHz] (to be improved)

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]

Hydrophones: Tested and calibrated for 3500 m

Preamp: 32 dB gain, 0.8 nV/ √Hz input noise

ADC-board: 24 bits, 192 kHz sampling, 3 dB gain

Conclusions(part I)

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

Technological R&D:

Commercial Hydrophones available, can be calibrated as a function of pressure

Custom hydrophones reach good sensitivity, requires more investigation

"Synthetic neutrino pulse" emitters soon available

Test Sites:

Opportunity to test technology / software

Conclusions (part II)

Acoustic detection using the km^3 Cherenkov telescope infrastructure:

Acoustic positioning system is required in water, use it also for acoustic physics. The target, in my opinion, at this early stage of the acoustic detection techniques, are the GZK neutrinos. Those are the "gold" combined opto/acoustic events, moreover an array of hydrophones could reconstruct the interaction vertex outside the optical instrumented volume allowing to better reconstruct the energy of the particle that cross only partially the detector.

Multidisciplinary activities

An underwater array of hydrophones at high depth is a unique opportunity for biologist, and geophysics communities (at least) => share the same infrastructure and manpower.

Personal Comment:

Though the studies on this technique are still in an early stage, its potential use to build very large neutrino detectors is appealing, thanks to the optimal properties of mediums such as water, ice or salt as sound propagator. It's of fundamental importance to look for hybrid events (acoustic/radio/optic) to validate the techniques and to perform intercalibration of the detectors.

Just a raw idea: possible neutrino event calorimetry ?

Acoustic system triggered by KM3NeT to reduce acoustic background (time and direction)