Development of acoustic devices for ultra-high energy neutrino detectors

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On behalf of the ANTARES collaboration

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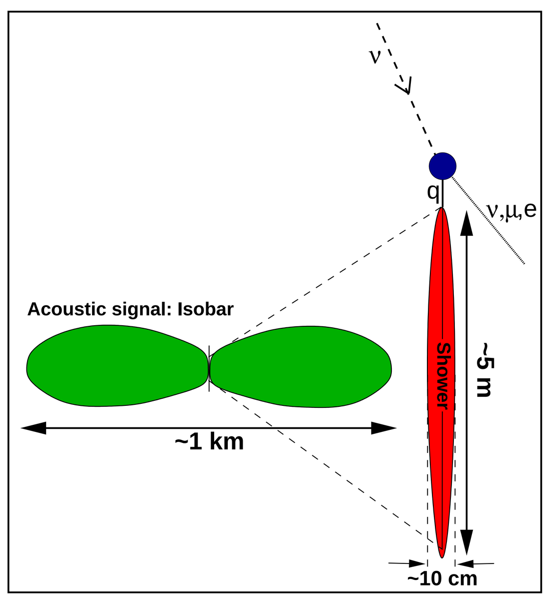
Neutrino fluxes at ultra-high energies (e.g. GZK neutrinos) are predicted to be very small. Thus large target masses are required to measure at least a few events during the lifetime of a typical experiment. The photo-sensor distance in water Čerenkov neutrino telescopes is limited by the attenuation length of the Čerenkov light in water or ice (50 − 70 m), constraining the affordable size of such detectors. Another approach to neutrino detection, allowing for detectors instrumented more sparsely, is the detection of acoustic signals produced by neutrino interactions. The sensor density in an acoustic detector is determined by the sonic attenuation length in water, which is about ten times larger than the optical attenuation length. In order to study the technical feasibility and environmental and background conditions of an acoustic neutrino detector, it is planned to deploy several acoustic sensors as part of the ANTARES neutrino telescope [1], which is being installed in the Mediterranean Sea, 40 km off the coast of Toulon.

Tests of the thermo-acoustic model

The thermo-acoustic model was first described by G.A. Askariyan in 1957 [2]:
A neutrino ν interacts with a target nucleon in the water producing an electromagnetic/hadronic cascade. The energy deposited in the water leads to a local heating of a few nK along the cascade. This induces a fast expansion of the medium, which propagates as a shock wave perpendicular to the cascade axis, giving measurable bipolar acoustic signals (typical frequency: 20 kHz) in the order of some mPa in a few 100 m distance (for a 1 EeV shower).
Given an deposited energy density $\epsilon(\vec{r},t)$ the pressure $p(\vec{r},t)$ can be calculated as:

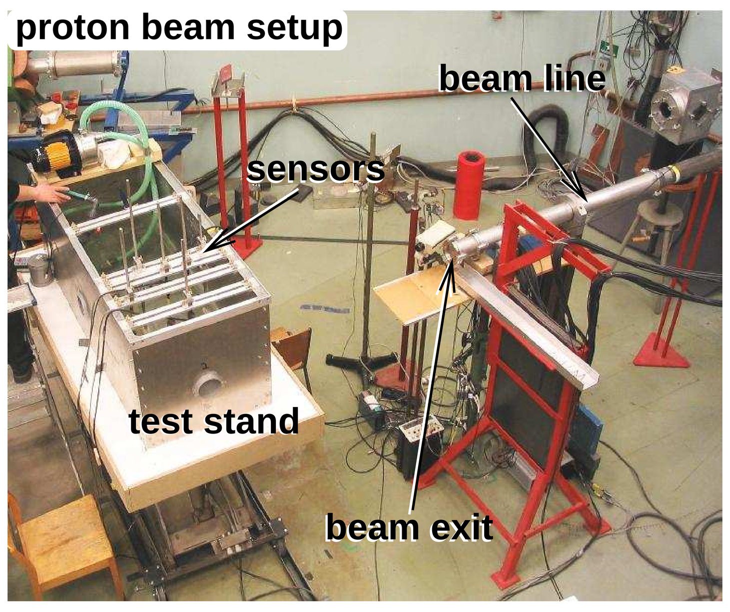
$$p(\vec{r},t) = \frac{\alpha}{4\pi C_p}\int \frac{d^3r'}{|\vec{r}-\vec{r}'|}\frac{\partial^2}{\partial t^2}\epsilon\left(\vec{r}',t-\frac{|\vec{r}-\vec{r}'|}{c_s}\right)$$

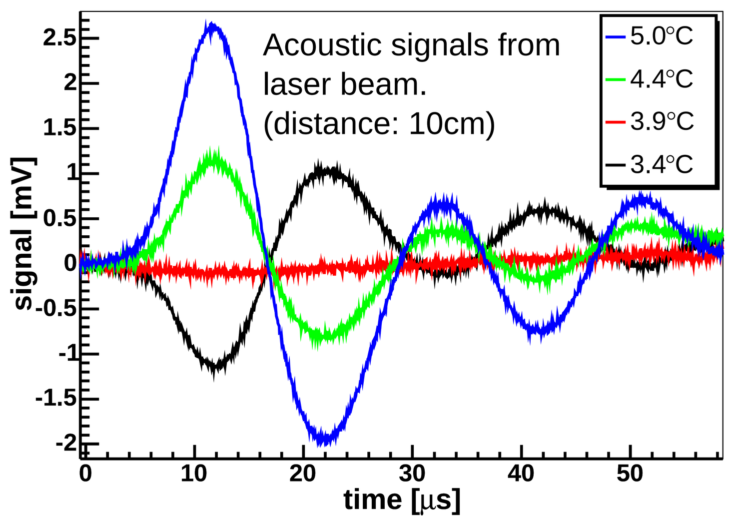
α: thermal expansion coefficient, C_p: specific heat capacity, c_s: speed of sound



The model was verified in laboratory experiments using a pulsed Nd:YAG laser, and the proton beam of the Gustaf Werner Cyclotron at the Theodor Svedberg Laboratory in Uppsala, Sweden [3]. The beams were dumped into a temperature controlled $150 \times 60 \times 60\,\mathrm{cm}^3$ water tank.

	Laser beam $\lambda = 1064$ nm	Proton beam $E_p = 177$ MeV
pulse energy	0.1 − 10 EeV	10 − 400 PeV
penetration depth	6 cm (absorption length)	22 cm (Bragg peak)
pulse duration	10 ns	30 µs
beam width	0.1 − 1 cm	0.6 − 2 cm



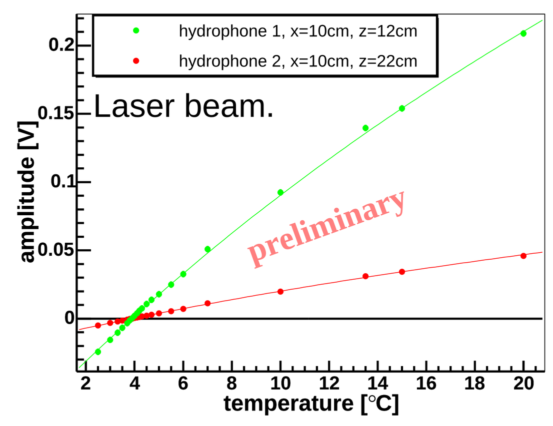


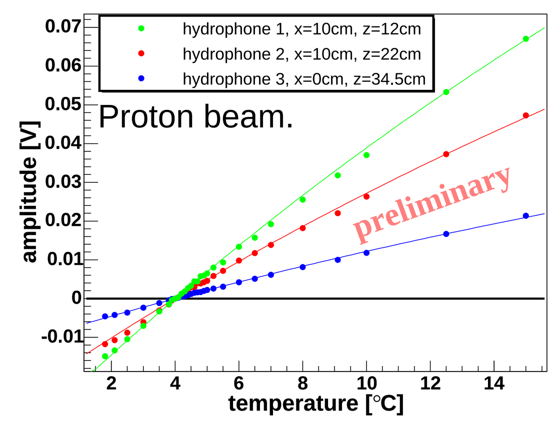
Results:

- measured bipolar signals are in excellent agreement with simulations made under the assumption of a thermo-acoustic signal generation mechanism
- laser beam signal vanishes as expected at 4°C (cf. left plot below) ($p(\vec{r},t) \propto \alpha$, and α_{H_2O} vanishes at 4°C)
- signals from proton beam show a residual of approx. 1 mV at 4°C, which never vanishes
- for the proton beam a non-temperature dependent effect on top of the thermo-acoustic signal is assumed

⇒ subtract residual signal from all proton beam signals
⇒ good agreement with model predictions

- signal dependencies on beam energy, beam width and sensor distance from the beam show all very good agreement with the expectations from the thermo-acoustic model





Development and characterisation of acoustic sensors

Acoustic signals in water are detected by hydrophones based on piezo ceramics. Two types of acoustic sensors have been studied: piezo ceramic elements coated with polyurethane, or mounted into pressure-tight vessels. The second option is particularly interesting when using glass spheres or titanium vessels that are housing the ANTARES components, since their water tightness is guaranteed, and they are easy to integrate into the existing ANTARES detector setup.

Goal:

- We want to be able to predict the acoustic properties of piezo ceramic elements and hydrophones using finite element methods to be able to develop hydrophones optimised for acoustic particle detection.

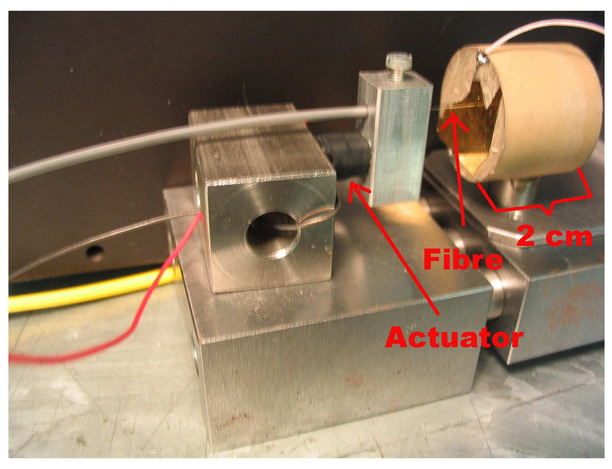
Electronic properties (Impedance):

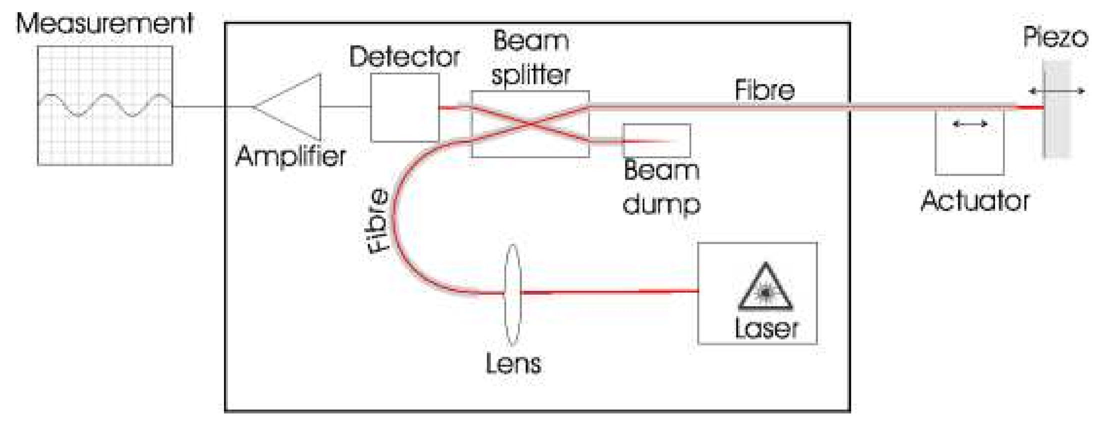
- is predicted from the known quantities permittivity, elasticity modulus, and piezoelectric modulus by using finite element methods
- is measured by
  - applying white noise to the piezo element
  - measuring the voltage at a capacitor in serial connexion
  - doing a frequency analysis

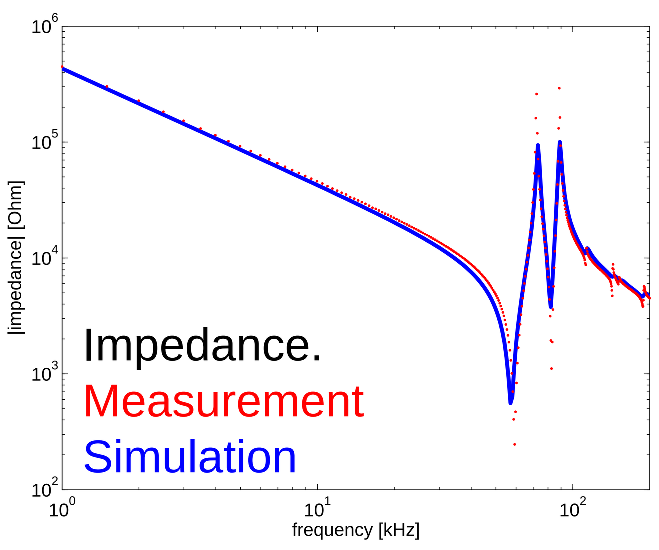
Mechanical properties:

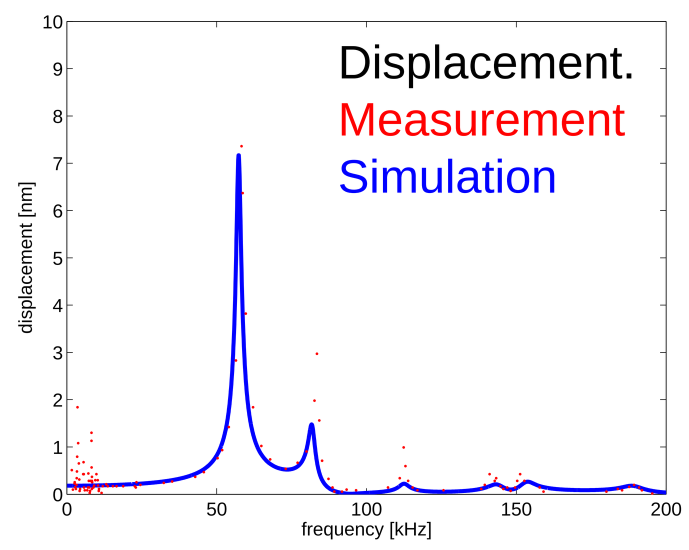
- measure displacement of piezo element surface as a function of frequency
- use Fabry-Perot interferometer (precision: 0.1 nm)

⇒ Detailed prediction of electronic and mechanical properties, including resonance frequencies, from material properties and piezo element geometry.

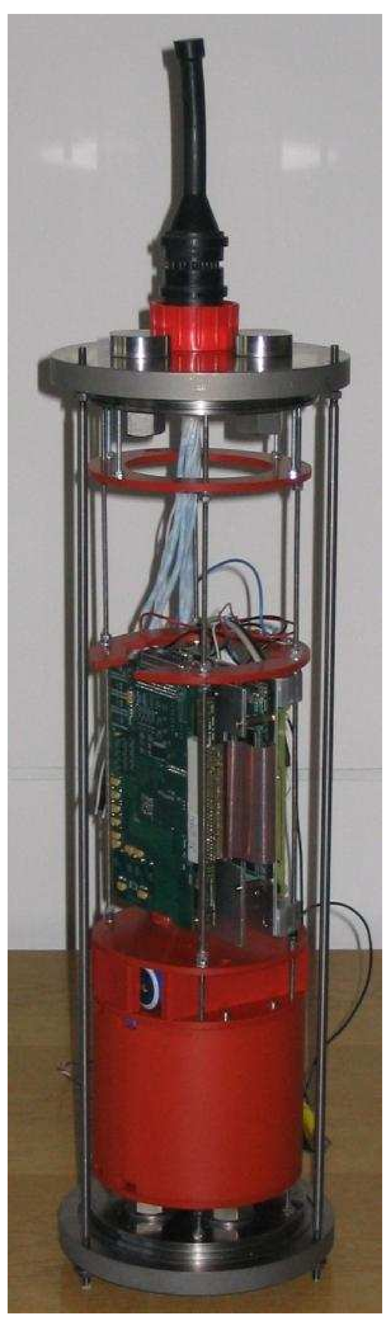








AMADEUS – Autonomous Module for Acoustic DEtection Under the Sea



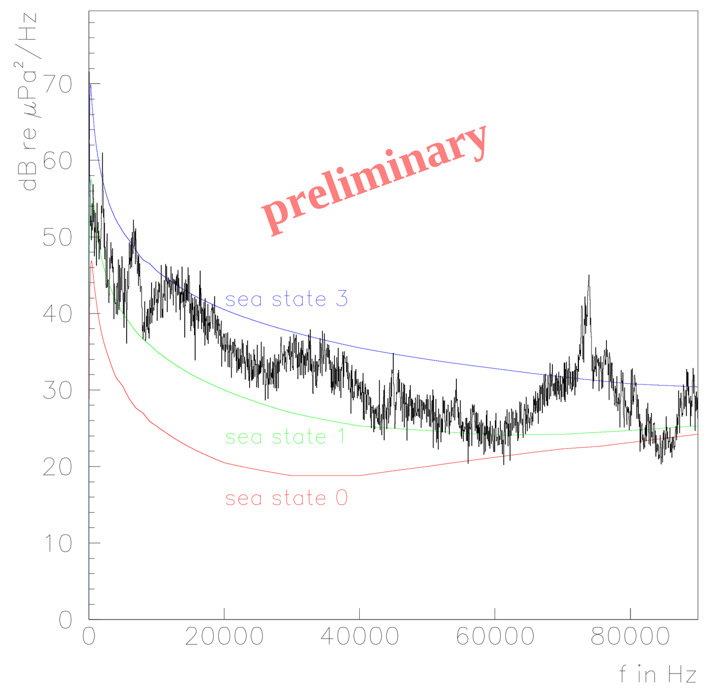
Motivation:

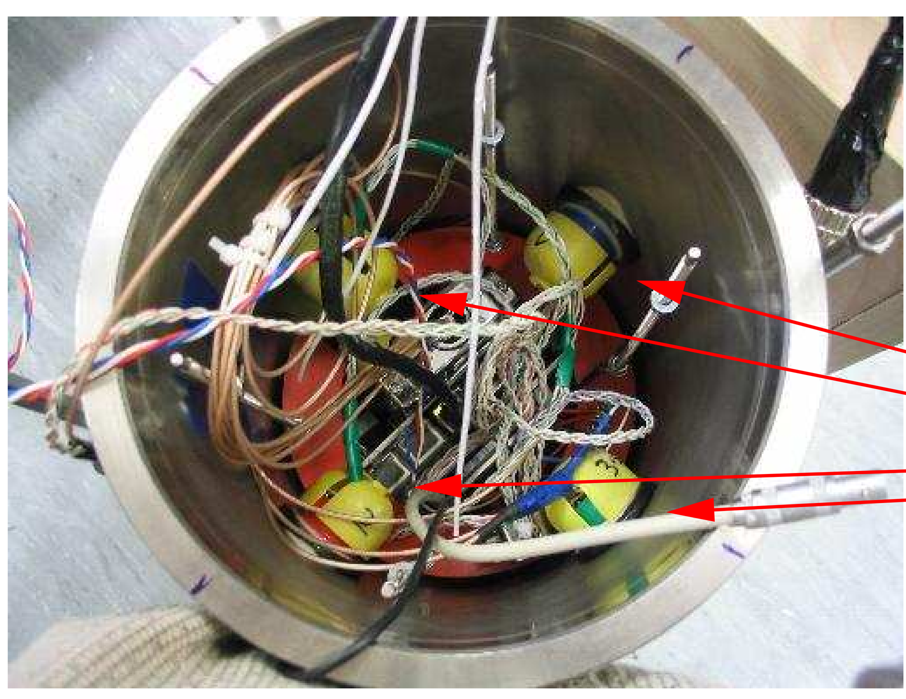
- For the development and operation of an acoustic detector, it is necessary to have good knowledge of the background properties at the detector site:
  - frequency spectrum
  - correlation length
  - nature of noise: white noise or many point sources?
- For sensor development, tests under realistic environmental conditions have to be performed.

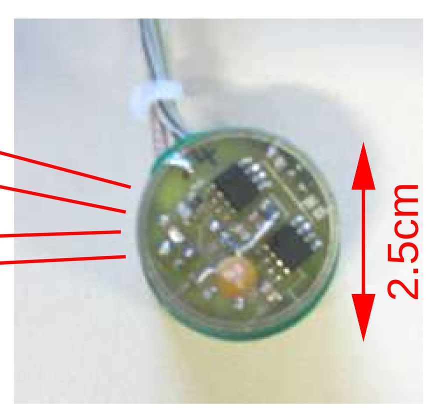
Setup:

- Autonomous DAQ system installed into a titanium container used for ANTARES electronics
- 5 piezo ceramics sensors glued to the titanium surface, and read out with a 16-bit ADC card (integral sampling rate 500 kHz)
- data written to flash card and copied to hard disk during non-data taking periods to suppress noise from hard disk vibration
- battery power for approx. 70 hours of data acquisition
- deployed and operated successfully in spring 2005 together with the ANTARES prototype string "Line0"

⇒ We have 12 hours of in-situ acoustic data for analysis







References

[1] http://antares.in2p3.fr/

[2] G.A. Askariyan, *Atomnaya Energiya* **3**, 152 (1957).
G.A. Askariyan et al., *Nucl. Inst. Meth.* **164**, 267 (1979).

[3] publication in preparation.

[4] R.J. Urick, *Principles of underwater sound*, Peninsula Pub. (1983).