Abstract. Acoustic particle detection techniques have experienced a strong revival during the last few years, but are still in an R&D phase. Progress has been made since ARENA2005 a year ago in particular in simulation techniques for particle energy deposition, sound generation and propagation as well as detector response. Also new signal processing and reconstruction techniques have been reported. Recent in-situ measurements allowed to study available transducers in natural environments. Several projects, to be realized during the next years, aim to deliver the basic input for future arrays of \( \sim 100 \, \text{km}^3 \) size. To study successfully highest energy cosmic neutrinos such arrays should use hybrid detection techniques, with optical, radio and acoustic sensors as basic elements.

1. Introduction

A recent simulation [1] showed that probably the best approach to measure highest energy neutrinos is to combine the advantages of different detection techniques in a hybrid devise. This will diminish background problems and increase the number of reconstructed events. Presently considered target materials are water, salt and ice. In the first two cases optical+acoustic and radio+acoustic detection is applicable. Only ice offers the unique possibility to use all three methods simultaneously.

In the preceding article of this volume [2] it is discussed in detail that radio sensors are already used in carefully designed experiments searching for the tiny fluxes of cosmic neutrinos. In fact these type of experiments presently give the best flux limits for neutrino energies above \( 10^8 \) GeV (see fig. 1) and may be the first to observe a few neutrinos created in proton interactions with the cosmic microwave background radiation [3].

Fig. 1 Flux prediction for different cosmic neutrino production models and corresponding best experimental limits from radio and acoustic experiments (from [6])
Another technique which offers promising capabilities to detect high energy neutrinos is the search for acoustic signals from neutrino interactions in dense target materials as predicted by the Thermo-Acoustic Model [4]. Many groups worldwide try to improve this technology in several R&D projects (see table 1) and the basic predictions of the Thermo-Acoustic Model are meanwhile sufficiently proven in several accelerator tests [5]. However, significant progress is still necessary to build large experiments based on acoustic sensors.

| Group                | Experiment | Activities                                      |
|----------------------|------------|-------------------------------------------------|
| Stanford             | SAUND      | data taking, signal processing, calibration, simulation |
| Moscow (INR1)        | AGAM, MP10 | signal processing, calibration, simulation      |
| Moscow (INR2), Irkutsk | Baikal    | signal processing, noise studies, in-situ tests at Baikal |
| Moscow (ITEP)        | Baikal, Antares | detector R&D, accel. tests, in-situ tests at Baikal, signal processing, noise studies |
| Marseille            | Antares    | detector and installation R&D, calibration, noise studies, simulation, |
| Erslangen            | Antares, KM3NET | detector R&D, accel. tests, calibration, simulation, noise studies, in-situ test measurements |
| Pisa, Firenze, Genua | KM3NET     | detector R&D                                      |
| Rom, Catania         | NEMO       | installation R&D, accel. tests, noise studies, simulation |
| Lancaster, London, Newcastle, Sheffield | Rona, KM3NET | simulation, signal processing, calibration, in-situ test measurements |
| U. Texas             | Salt Dome  | detector R&D, attenuation studies, material studies |
| Berkeley, DESY, Stockholm, Uppsala | IceCube | detector R&D, accel. tests, material studies, simulation, noise stud., in-situ test measurements |

Table 1: Groups active in acoustic R&D (green: contributions to this conference, light blue: related to military hydrophone arrays)

Only the SAUND group published a neutrino flux limit [6] restricted to very high energies and still not competitive with radio detector results as seen from figure 1. SAUND uses hydrophones of an existing military array near the seabed as other groups did before [7] and do presently [8]. This offers the possibility to study in-situ acoustic properties of water as a target and signal propagation medium. In particular the measurement of acoustic background noise gives important information. First signal processing and reconstruction studies are possible. However, these arrays are optimized for a different purpose and therefore don’t fit several requirements for cosmic neutrino detection, like frequency range, geometrical arrangement and water depth.

Increasing efforts exist at several sites to build large acoustic detector arrays which are adapted to the needs of high energy neutrino search. A first overview about these activities was given last year at ARENA 2005 [5]. Groups that presented new results now one year later are indicated in table 1. Particular attention was paid this time to simulation studies to find optimal experimental conditions as well as to build high sensitivity and low self-noise devices which allow to decrease the present energy threshold for applications at least by an order of magnitude. Next steps are taken to build small arrays to study in detail the basic needs of 100 km³-scale acoustic experiments, which possibly could be realized in a decade from now.
2. Simulation of acoustic sensor array sensitivity

This topic has rather different ingredients. First one has to understand, how neutrinos, photons, electrons and hadrons interact with matter at highest energies and how further generations of particles from such interactions deposit their energy in space and time. This is dominantly a particle physics problem and a basic uncertainty arises from presently poor knowledge of hadronic cross sections and interaction dynamics above energies of $10^{15}$ eV. New measurements that are planned at the LHC may improve the situation during the next years [9]. The shape of the energy deposit of hadronic or/and electromagnetic cascade is what finally determines the strength and frequency of the primary acoustic signal [4]. Another topic is that the sound propagation through the target material has to be understood, strongly influenced by material and environmental conditions often known only from theoretical estimations [10]. At the end assumptions about acoustic detector threshold, noise conditions and trigger scenarios have to be made to calculate detectable flux limits. Several contributions to this conference presented corresponding new results.

For the simulation of neutrino interactions with matter often the GEANT package [11] is used, applicable unfortunately only up to energies of about 10 TeV. To overcome this problem, several parametrizations have been developed giving information about the cascade energy deposit [12,13] at higher energies. A new approach has been presented at this conference by T. Sloan. The CORSIKA program [14], originally developed for the simulation of air showers produced by charged cosmic particles, has been successfully modified to be used with water as interaction target. All advantages of the program package developed over years are thus available for the simulation of compact cascades. It will be easy, for instance, to study the influence of the LPM-effect [15] at highest energies. A detailed comparison of GEANT4 and CORSIKA based results for proton interactions in water at 1 TeV has been performed. From figure 2 it can be seen that CORSIKA showers are slightly broader and more elongated at low energies.

V. Niess has also shown new results on the energy deposit of high energy particle cascades and corresponding signal shape and strength following the approach in [12]. For electron neutrino interactions the hadronic cascade is visible for charged and neutral current processes, but in the first case overlaid by a fuzzy long LPM-tail as can be seen in figure 3.

J. Perkin presented results from a complete acoustic simulation chain, including signal reconstruction (discussed in more detail in the contribution of S. Bevan) and signal filtering the importance of which was exemplified by S. Danaher. Special attention was paid to refraction that leads to a deformation of the acoustic wave passing the array. Taking into account this effect requires time consuming algorithms using look-up tables, but is necessary to calculate the direction of the incoming neutrino with sufficient precision. The derived flux limit for a 30x50x1 km$^3$ acoustic array agrees nicely with the result of an independent simulation based on similar assumptions [16].
3. Simulation of acoustic sensors

In order to design and optimize sensitive acoustic sensors and transmitters for application in different media it is desirable to have tools at hand to simulate the sensor response. Particularly in water it is important to reproduce the bipolar signal shape that is expected from a neutrino induced thermo-acoustic pulse. This needs a linear phase response of the hydrophone amplifier/filter system as strongly underlined by S. Danaher. In this case the received pulse is only delayed. If the phase response is non-linear, distortions will occur as can be seen from figure 4.

C. Naumann reported about the simulation of complex piezo sensors based on the electro-mechanical equivalent principle. Mechanical properties of piezo elements can be expressed by equivalent electrical ones. This is schematically shown in table 2 ($\alpha$ denotes the material dependent electro-mechanical coupling constant). In this way e.g. the impedance vs. frequency spectrum of a piezo element can be determined, reflecting the resonance behaviour due to its geometry and material properties. The resonances are damped if the piezo is strongly coupled to an outside medium. The impedance measurements lead to predictions about the sensor sensitivity in good agreement with direct measurements (see figure 5). Predictions of the signal response need knowledge of the system transfer function that also includes the phase response. Comparing measurements with model predictions this function can be determined. In figure 6 it is demonstrated that the corresponding calculated signal shapes agree well with observations.
K. Salomon aimed to get a microscopic understanding of piezo ceramics behaviour. Using the finite element method he solved the system of partial differential equations for the motion of piezo elements coupled to an anisotropic medium. The results are compared to direct measurements of the displacement using a custom-build fiber coupled interferometer and with simulation results of the electro-mechanical equivalent circuit method. In both cases good agreement is found.

4. Calibration of acoustic transducers
The calibration of complex devices remains a necessity for future use in UHE neutrino detection. M. Ardid presented a study about the absolute calibration of acoustic sensors using the reciprocity method. Usually the free field configuration is used, which is not easy to realize in the laboratory. Several techniques have been considered to avoid the corresponding limitations. Simulation results still reveal big uncertainties that may be reduced in the future. The reciprocity method may be used to calibrate the sensors of a large neutrino telescope just without the need for a dedicated transmitter. This would be of particular importance for a huge array imbedded in ice, as suggested in [1].

The calibration of acoustic sensors and transmitters for the SPATS project was described by F. Descamps. Here a relative calibration with respect to the known absolute sensitivity of a commercial hydrophone was performed. To avoid wall reflections the corresponding measurements took place in a large water tank (12x10x5 m³) by transmitting a short pressure pulse to the sensor located 1 m away. The frequency spectrum and the phase response in the complex plane was calculated via Fourier transformation of the signal. The data allowed to determine the absolute pressure vs. frequency output of SPATS transmitters and, using this information, to calculate also the absolute SPATS sensor sensitivity in water. Measuring in addition the self-noise of the sensors allows to derive the equivalent self-noise levels of the detectors, important for the minimal possible trigger threshold of the devices. In figure 7 the range of the equivalent noise levels is given for all SPATS detectors together with the commercial hydrophone used in the calibration. An improvement of about a factor 10 could be reached for nearly all frequencies. A question still open for SPATS is how to do the calibration of transmitters and sensors in ice.

5. In-situ measurements and future projects
Since more than five years two groups perform acoustic studies at lake Baikal at the location of the NT200+ neutrino telescope. Beside intensive noise studies both try to identify acoustic signals in events triggered by a large air-shower array. Corresponding reports were given already at ARENA 2005 [5]. In the meantime the proposed four hydrophone antenna module has been deployed by the BAIKAL team in a depth of 100 m and started data taking in April of this year [17]. New results of the
ITEP group were reported at this conference by V. Lyashuk. Data from excursions of four years taken with a four hydrophone string near the ice surface have been analyzed. The acoustic antenna was triggered by an EAS array on top, consisting of seven scintillation counters. Two different methods are proposed to extract small acoustic signals in a noisy environment. The basic idea is to look for signal induced changes in the shape of noise in the time-domain [18]. No EAS related events could be observed until now.

On behalf of G. Riccobene, A. Capone presented first results from the NEMO test site in the Mediterranean, at 26 km distance from Catania in 2000 m depth. The Ocean Noise Detection Experiment - OvDE - has been deployed here in January 2005. Four hydrophones took data since then for five minutes every hour. Three of these devices were calibrated and measured about the same noise level – better than sea state 2 – with many short time variations but stable long term behaviour (see figure 8). Calibrated signals transmitted from a nearby vessel were well received. In addition sperm whale clicks were discovered and opened the door to interdisciplinary research together with maritime biologists.

In two talks K. Graf reported for R. Lahmann and himself about the use of the ANTARES framework to evaluate the prospects of an acoustic neutrino detector. For 2007 it is planned to deploy three acoustic storeys at the ANTARES instrumention line from 2180 to 2300 m as shown in figure 9. The arrangement allows to use local coincidences for directional reconstruction and study noise as well as signals from calibrated sources. More acoustic storeys are foreseen to be added to one of the last deployed ANTARES strings. This will allow to test realistic three-dimensional reconstruction for a later 100-1000 km$^3$ array.

The technical solution for the acoustic addition stays as close as possible to the implementation of the optical detector. Hydrophones are added either directly to the storeys mechanical frames (figure 9) or inside the pressure spheres normally used to house the photomultipliers. The ANTARES digitization boards are replaced by dedicated "acoustic" ADC’s. The digitized information is afterwards transported to the shore station via the deep sea cable, awaiting further processing.

First data taking with the RONA array, a British MoD facility in North West Scotland, was described by S. Danaher. Eight hydrophones instrumented for high frequency continuous data acquisition are located in different depth in the 200 m deep sea. The hydrophones are commercially available with wide frequency band and almost linear phase response. First data were taken for 15 days in December 2005. Applying trigger and filter algorithms the data could be reduced by about two orders of magnitude. Several filter schemes were tested, an example is shown in figure 10. Finally $2.3\times10^5$ events remained for further analysis. Due to its extension of 1.5 km a trigger window for
coincidences of about a second had to be applied. Vertex reconstruction was tested to discriminate noise events, but even for five-fold coincidences too many random triggers were found in the large time window. A few “golden” events were identified, one of them is shown in figure 11.

L. Thompson described future plans for RONA data taking. Starting in September 2006 more data will be acquired to improve the understanding of the hydrophones in different sea states and climate conditions and study event filtering and reconstruction algorithms. A new data acquisition system with audio compression utilities will be used. In addition the ACoRvE group wants to build an acoustic simulator for RONA which produces pulses which are received as bipolar signals at the hydrophones. Finally a special transmitter array should be built which creates a “bipolar pancake” like a real UHE neutrino interaction.

R&D studies for a large hybrid neutrino detector at the South Pole need knowledge of the acoustic attenuation length, velocity of sound and noise levels at different depth in the ice. To measure these quantities the “South Pole Acoustic Test Setup” - SPATS – has been designed. A schematic view of the setup is shown in figure 12.
S. Böser reported about the status of the project. Three strings of 400 m length carry seven detector modules with transmitter and receiver units, each. Signals are transmitted homogeneously in azimuthal angle. The receiver units contain three piezo sensors with 120 degree angular spacing allowing for some directional sensitivity. Registered signals are digitized directly on top of the string from where the data are transferred to a master PC.

Several tests have shown the capabilities of SPATS under extreme conditions. Transmitters and sensors as well as the string DAQ have been placed in a laboratory freezer for two months at -50 to -70 ° C. Booting was possible even after having switched of the system for more than a day. Outdoor tests at lake Torneträsk in the North of Sweden showed the transmitter and receiver capabilities over long distances. At the maximum available cable length of 800 m still a signal to noise ratio of more than 5 was measured as can be seen from figure 13, well sufficient for the planned measurements at South Pole. SPATS is foreseen to be co-deployed in three holes drilled for the IceCube experiment [19] in January 2007. First results can be expected in the summer of the coming year.

6. Final remarks
Acoustic particle detection is still a research field of growing interest of astro-particle physicists. Since last years ARENA 2005 workshop several new groups joined, already existing ones widened their activities. Progress is made in all parts of simulation, detector design, signal processing and reconstruction. Lots of new data will be available in the near future from in-situ tests in the Atlantic Ocean, the North Sea, the Mediterranean, Lake Baikal and the South Pole. Extensive studies of material properties and background noise levels will be possible in that way at different environmental conditions. This will deliver the basic information for the design of a ~100 km³ detector array that is necessary to measure the small fluxes from ultrahigh energy neutrino sources. To build such an array seems to be in reach until the end of this decade. The next ARENA conference - promised to take place in two years from now in Italy - will hopefully allow to get a much clearer view of this vision.

Acknowledgement
During the three days of this conference 50 physicists from 10 different countries around the world had the possibility to hear talks about important R&D activities and ongoing experiments of the field. Equally important was the possibility to meet colleagues for intensive and detailed discussions. The conference dinner in Lumley Castle will be unforgettable. ARENA 2006 was a big success - very many thanks to the organizers of this conference, Lee Thompson, Sean Danaher and their whole team, for making all that possible.
References

[1] D. Besson et al., Int. J. Mod. Phys. A21S1:259 ,2006 astro-ph/0512604, submitted to Astroparticle Physics
[2] D. Besson, “ARENA 2006 Conference Summary – Radio Detection”, this proceedings
[3] S. Hoover, contribution to this proceedings
[4] G.A. Askaryan et al., NIM 164(1979)267, J. Learned, Phys.Rev. D19(1979)3293
[5] Proceedings ARENA 2005, ed. R. Nahnhaeur and S. Boeser, World Scientific, 2006
[6] J. Vandebroucke et al., Astrophys.J. 621(2005)302
[7] Y. Karlik et al., Proc. XXXII Recontres de Moriond, ed. J. Tran Tranh Van, Edition Frontiers, (1997)283
[8] S. Danaher contribution to this proceedings
[9] O.Adriani et al., CERN-LHCC-2006-004, 2006
[10] P.B. Price, Jour.Geophys. Res., Vol 111, B00002201,2006
[11] S. Agostinelli, NIM A 506 (2003)250; J. Allison et al., IEEE Tr. Nucl.Sc.53 (2006)270
[12] E.Zas et al., Phys.Rev. D 45 (1992)362, J.Alvarez-Munisand E. Zas, Phys.Lett. 441 (1997) 218 and 434 (1998) 396
[13] L.G. Dedenkov et al., in [5] page 45
[14] http://www-ik.fzk.de/corsika/
[15] L. Landau and I. Pomeranchuk, Dokl. Akad.Nauk SSSR 92(1953)553 ; 92(1953)735 A.B. Migdal, Phys.Rev. 103 (1956)1811; Sov. Phys.JETP 5 (1957)527
[16] T.Karg et al., in [5] page 212
[17] R. Wischnewski, private communication
[18] V. I. Lyashuk, E.G. Novikov, to appear in Russian Nuclear Physics, 2006
[19] A. Achterberg et al., Astroparticle Physics 26 (2006)155