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Studies of underwater acoustic detection of ultra-high energy neutrinos in ANTARES

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The ANTARES collaboration is deploying a 2500 m depth underwater neutrino telescope in the Mediterranean Sea off shore from Toulon (France). The Cerenkov light emitted by high energy muons (above few GeV) originating from neutrino deep inelastic scattering is detected by photomultipliers. An alternative detection method of ultra-high energy 10^{18+} eV neutrinos is to record the ultra-sonic pressure wave generated by neutrino induced particle showers in sea water. Because acoustic waves have a kilometric attenuation length in water this method allows the detection of long range events occurring in a large volume of sea water. To develop this detection method a precise knowledge of in-situ deep sea underwater ambient noise is required. Therefore the newly deployed ANTARES instrumentation line MILOM is equipped with an hydrophone with dedicated digitization and shore transmission electronics, in order to monitor ambient acoustic activity over several seasons.

1. Introduction

It has been suggested in 1957 by G.A. Askariyan [1] that high energy particles cascades could be detected from the acoustic wave they generate when showering in a dense media. With the development of acoustic underwater neutrino detector projects this idea has been more intensively investigated, both experimentally [2] and theoretically [3]. From proton beam experiments it was established that the primary acoustic emission from the cascade should be of thermal expansion origin. The fast heating of the water volume results in a pressure wave expansion pulse whose characteristic duration is related to the lateral distribution of particles among the cascade. Due to the high asymmetry of the cascade energy deposition area the acoustic radiation is strongly coherent only in directions normal to the axis of the shower.

Recent estimations [4], take into account ambient sea noise, enhanced absorption loss due to sea water chemical composition, and reconstruction issues from the strong directivity of the signal. They agree that in sea water the acoustic method can become effective only at the highest energies. At these energies it is also necessary to take into account the Landau-Pomeranchuk-Migdal suppresion effect [5] leading to shower extensions ranging from a few tens of meters to several hundreds of meters.

2. Acoustic signal characteristics

The fast energy deposition combined with a narrow lateral distribution among the shower act as an impulse acoustic source. A ‘strong’ fast compression impulse is emitted followed by a weaker and slower rarefaction relaxation. Characteristic duration in close range of a few meters from the shower could be as small as a few hundred nano-seconds. However sea water is a dissipative medium which is refractant to the propagation of high frequencies with absorption lengths of about 1 km around 30 kHz. Hence on kilometric ranges the shape of the acoustic signal from showers is strongly determined by the absorption impulse response of the medium. At these distances absorption loss in sea water is dominated by a coupling to the dissociation equilibrium of sulfate magnesium (MgSO4) as was first described by Liebermann [6].

This results in an asymmetric Gaussian like shape of the acoustic pulse, with a characteristic duration Δt increasing with range ρ as $\Delta t = 16\ \mu\mathrm{s}\sqrt{\rho / 1\ \mathrm{km}}$. The amplitude A of the signal decreases as a power law with respect to the distance ρ to the shower axis as $A \propto 1/\rho^{\alpha}$. The values of the exponent α can vary from 0.5 to 2, depending on shower extension and distance. The ratio of the amplitudes of the leading compression to the rarefaction pulse also varies with distance and cascade extension. The signal becomes more and more symmetric as the ratio of distance to shower length increases. This results from a higher frequency content of the compression pulse, hence being more strongly affected by absorption with increasing range. The combination of signal duration and asymmetry could be used to estimate the elongation of the showering acoustic source.

At kilometric distances the amplitude of the signal is predicted to be of some mPa for ultra-high energy primaries. However uncertainties of at least a factor of two arise from the knowledge of the shower development and its shape. Furthermore competitive acoustic production mechanisms, possibly more efficient might play in [7].

Whatever, the efficiency of this acoustic method will depend on the ability to distinguish these pulse like signals from ambient acoustic noise and to extract information on the shower characteristics.

3. Ambient noise

Ambient sea noise has been extensively studied during World War II [8] in the frequency range of some hundred Hz up to 10 kHz. In this range the noise originates mainly from the relaxation of bubbles, introduced by breaking waves at the surface of the sea. Therefore it is dependant on surface wind speed or sea state. The resulting spectral density is known to decrease as a power law with frequency with an exponent of about 0.85. At higher frequencies, above 30 kHz, ambient noise is predicted to be dominated by water molecules thermal motion. In between they should be a window for low ambient noise conditions in particularly at depth, far from the surface. However at these low noise spectral densities of some 10 $\mu\mathrm{Pa}/\sqrt{\mathrm{Hz}}$ one reaches the piezo-ceramic transducer self noise level, leading to technical issues.

Furthermore one is interested in the detection of impulse like signals which requires a specific shape characterization, since spectral densities are ambiguous. In addition biological noise might also mimic the signature of a neutrino. In particularly snapping shrimps and mammals are known to emit strong acoustic signals in the ultra-sonic ranges. Lastly, because even with tens of cubic kilometer volumes the expected events originating from UHE neutrino interactions are thought to be rarer as a few events per year, it is also necessary to survey noise on long term periods. Therefore a dedicated hydrophone set-up, christened Spy Hydrophone, was deployed on the MILOM instrumentation line of the ANTARES detector.

4. The Spy Hydrophone setup

The pressure sensitive element of the set-up is an hydrophone that was developed at the request of the ITEP institute for the purpose of acoustic detection studies in Lake Baikal [9]. The transducing part of the hydrophone is a cylindrical piezo-ceramic of 5 cm height and 3 cm diameter. The cylinder is a few mm thin which results in low equivalent noise level of a few $\mu\mathrm{Pa}/\sqrt{\mathrm{Hz}}$. The sensitivity of the piezo-ceramic is 1 mV/Pa. The ceramic is backed by a low noise pre-amplifier of 28 dB gain. First order band filtering allows for a flat global transducing response in the frequency range of 10-50 kHz. The hydrophone was fixed on the top storey of the MILOM line, 165 m above the sea bed, hence at 2310 m depth. The hydrophone was calibrated at IFREMER-Brest, France and its impulse response was modelled from measurements using an opto-acoustic laser setup in Erlangen, Germany.

The data acquisition electronics is composed of two boards located in a standard ANTARES titanium container on the same storey than the hydrophone. The first board is an amplifier with a variable gain of 40 dB dynamic that was developed by the French company OSEAN. The second board was developed at CPPM. It contains an analogic to digital sampler (ADC, Burr Brown ads8322) that is clocked by an Altera FPGA (Altera 10K50E) and a micro-controller with embedded Ethernet (RCM3200 RabbitCore). The micro-controller allows for remote control of the different electronic parts through an optical fibber link that connects the ANTARES MILOM line, at 2.5 km depth in the Mediterranean Sea, to a shore station 40 km away in La Seyne sur mer, France. The electric to optical conversion is done by an Ethernet bi-directional link (BidiPhoton) located on the second board.

The global characteristics of the system are as following: Data can be sampled at 400 or 200 kHz with a 16 bits resolution. At 400 kHz time slices of 0.5 s of continuous data are send to shore every 1.5 s. The dead time in the acquisition comes from the micro-controller that is not fast enough to simultaneously read data from the ADC and send them via Ethernet within the time of the data sampling. Alternative solutions using several micro-controllers are currently investigated. Data slices are time-stamped off-shore by the FPGA which is monitoring the ANTARES clock signal. The accuracy was set to 1 µs, which is enough considering the data sampling rate. Note that jitters smaller than 100 ps are achieved by the ANTARES clock system. Absolute timing, as regard to UTC time, of a few micro seconds is achieved.

In optimal working conditions the equivalent self noise level of the whole set-up would have been of some hundred µPa in the frequency band of interest. However, several acoustic calibration measurements have shown that the hydrophone is not working optimally. The disablement is suspected to be due to the amplifier which might have been burned by a shortcut on the common powering in the electronic container. Whatever the origin, consequences are that the whole sensitivity of the device is of several tens of mPa, so about 40 dB worst than expected. In conjunction with the low frequency band filtering this results in the fact that we are not sensitive to surface noise conditions. Furthermore high frequency electronic noise pickup limits the detection capabilities for impulse like signals. Nevertheless, apart from the signal to noise ratio, critical though, the set-up is operating well and several ultra-sonic strong sound sources have been recorded.

3. Acoustic measurements

Data are sent to shore and analysed in real time using a PIV 2.4 GHz computer. An analysis of time-slices based on a FFT, with a 320 µs (128 samples) gaussian sliding window, is used in order to trigger data on a threshold comparison. This is a particular wavelet transform and generates a spectrogram of data. Since it is not possible to store over a year all the data sent to shore we apply a data reduction strategy based on a minimum bias trigger. Every 120 s, whatever the trigger condition the data slice is kept, otherwise if no other trigger condition the data is thrown away. This allows for a reduction by a factor of 80 of data rate with possible monitoring of slow variations in ambient noise conditions. At the time of the writing 20 GB of data have been taken with this strategy. 2000 events have been triggered which represents a rate of about 10 trigger/h. However, trigger events are not uniformly distributed over time and mostly occur in bursts. Several classes of events have been identified. A few are isolated pulses, hence neutrino like signals. But the acoustic origin of these pulses is yet uncertain.

In addition the time-stamping of the data allows for correlation studies with other devices located on the MILOM line, or with Astrophysical alerts, like GRBS. This is currently under study.

4. Outlook

The use of an acoustic antenna of at least four hydrophones could give good insight on the origin of noises. By using four or more hydrophones in close range of some meters it is possible to measure the local direction and speed of a assumed coincident event. Due to the short duration and the bipolar shape of the signal we look for, relative accuracies less than one percent can be achieved. By correlating to a measurement from a sound velocimeter one can precisely assesses on the acoustic origin of coherent sound speed coincident pulse like event. In addition, in the case of shower acoustic signal, the direction of propagation is strongly correlated to the direction of the primary since the pressure wave is propagating almost normal to shower axis. Refraction alters the picture for long range events. Direction is bent by an angle depending on range and cascade direction as regard to the vertical sound velocity gradient. Maximal deflections of 0.5 º/km are reached in the Mediterranean Sea. But for long range events distance could be roughly estimated from signal duration allowing for approximate corrections. Surface and bottom reflections might also complicate the picture. Surface reflections inverse the polarity of the signal. Nevertheless it is thought that one can already learn much from the use of a geometry optimized setup with a few sensitive hydrophones only. The use of larger structures in coincidence, while certainly required for UHE neutrino investigation, is thought little efficient on the basis of detection volume per hydrophone, due to the strong directivity of the signal.

4. Conclusion

Apart from a sensitivity loss on the transducer the dedicated Spy Hydrophone setup installed on the MILOM ANTARES instrumentation line is operating well. Observation of neutrinos cascades in these conditions is very unlikely. However useful experience is gained in the knowledge of the acoustic environment on the site. Some tricky strong impulse like signals have been detected but multiple hydrophones are required to further study their acoustic origin.

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