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STUDIES ON THE CONCEPTUAL DESIGN OF AN ACOUSTIC SENSORS ARRAY FOR NEUTRINOS EVENT TRIGGERING

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ABSTRACT

Neutrinos, although abundant in the Universe, are the most difficult Standard Model fermions to detect. Optical phenomena, such as Cherenkov light, are currently the main techniques for detecting neutrinos. However, it may be possible to detect ultra-high-energy (UHE) neutrinos using acoustic methods that detect their interactions with the medium, by means of characteristic pressure bipolar pulse in a medium such as water, whose properties may be detectable and analyzable. In this paper, we propose the development of an acoustic antenna consisting of an array of four synchronised hydrophones. This antenna will primarily be used to explore the possibility of detecting acoustic events such as bipolar pulses. Beyond the observation of UHE cosmic neutrinos the antenna will allow it to study other relevant acoustic phenomena such as those produced by geophysics, bioacoustics or anthropogenic noise, widening the field of application.

Keywords: *Neutrino detection, acoustic detection, hydrophone array, sea acoustic monitoring.*

1. INTRODUCTION

Neutrinos are minuscule and enigmatic elementary particles of the Standard Model of particle physics. They are generated in a variety of processes, including nuclear reactions in stars, supernova explosions, and even man-made processes such as nuclear power plants. Despite their abundance in the universe (the second most frequent after photons), they are very difficult to detect, due to their properties such as the absence of electric charge, a minuscule mass and interaction through the so-called weak interaction. Nevertheless, its study is imperative to comprehend the universe's structure and the fundamental processes that regulate it. There are several research infrastructures around the world dedicated to the study of neutrinos through the observation of physical phenomena that allow their detection. One way to study neutrinos is through the Cherenkov effect, a cone of bluish light induced by charged particles, e.g. muons, produced when the neutrino interacts with a particle in the medium. The cone axis gives the direction of the particle, and the light yield correlates with the energy of the particle [1]. An alternative method - acoustic detection - may offer a complementary approach to studying UHE neutrinos (1 EeV or larger). When neutrinos interact with a medium such as water, they create a localized energy deposition that leads to rapid thermal expansion. This expansion produces a characteristic pressure wave, known as a bipolar pulse (BP), which propagates through the medium and can be detected using specialized acoustic sensors. If used successfully, this technique could expand the possibilities for neutrino detection [2]. Our proposed sensor arrangement is based on experiments and previous experiences from research teams such as those at the Istituto Nazionale di Fisica Nucleare (INFN), which has been conducting underwater acoustics studies for over 20 years. In particular, we highlight monitoring system versions connected to a ground station, such as the NEMO-OνDE and SMO-OνDE-2 [3] stations, as well as autonomous systems such

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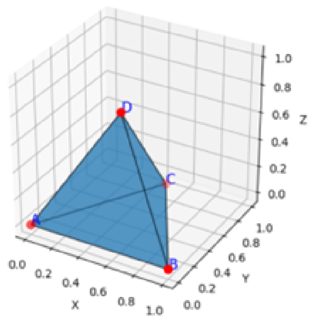

Figure 1: Receivers distribution

as IPANEMA-PANAREA [4] and the proposal submitted in the Conference on Technologies for Marine and Coastal Ecosystems 2024 [5]. Our sensor array will be distributed in a three-dimensional configuration, consisting of three hydrophones at the base and one outside the plane, forming a tetrahedral structure (see Figure 1). This procedure proposes the design of an array of acoustic sensors whose main objective is to trigger event detection based on specific acoustic patterns in order to store the data associated with candidate events. This proceeding is structured as follows. Section 2 describes the methodology used. Section 3 presents the estimation of the optimal sensor spacing. In Section 4 applications of the device beyond acoustic neutrino detection are discussed. Section 5 includes both conclusions and a list of next steps.

2. METHODOLOGY

According to Monte Carlo simulations, when a UHE neutrino interaction is produced in water, a 15 µs bipolar pulse is propagated mainly in the perpendicular plane of the neutrino direction with an amplitude of the order of mPa at a distance of 1 km [6]. However, its precise characteristics are not yet experimentally verified. Since our system operates passively, we will use a method based on Difference Time of Arrival (DToA) rather than time-of-flight measurements.

- Estimation of the position of the event: knowing the positions of the receivers, one of them defined as reference usually the first one with a positive detection, and the delay values between signals obtained by correlation, we apply a method for position estimation based on the $DToA$, as is the multilateration. The distances between the receivers and the emitter can be described as follows (see Equation 1):

$$\sqrt{(x_{R_i}-x_E)^2-(y_{R_i}-y_E)^2-(z_{R_i}-z_E)^2} - \sqrt{(x_{R_j}-x_E)^2-(y_{R_j}-y_E)^2-(z_{R_j}-z_E)^2} = C\cdot \mathrm{DToA}_{R_iR_j} \quad (1)$$

Where are the $x_{R_i}, y_{R_i}, z_{R_i}$, are the coordinates of receiver R_i, $\mathrm{DToA}_{R_iR_j}$ is the delay between receivers R_i, R_j and C the sound velocity. The solution to this system of equations results in the estimated positions of the source/emitter x_E, y_E, z_E.

- To obtain the $DToA$, we perform a cross-correlation between each possible combination of the raw signals recorded by the receivers to which we previously applied a synchronized cut-off window from a reference time ($ToAref$); we obtain a correlation peak and the corresponding delay or $DToA$, our case with four receivers we obtain three values.

- Raw signal cutout: knowing the distances between receivers, we can also determine the maximum difference in arrival times that a received signal will have at each receiver. This allows us to define a time window size for coincidences (see Equation 2) that will be used to crop each original signal starting from the ToAref, thereby reducing data storage needs.

$$\mathrm{WS_{ij}} = \mathrm{Dist_{ij}} + \mathrm{T_{uncert}} \quad (2)$$

Where $\mathrm{WS_{ij}}$ is the window size, and $\mathrm{T_{uncert}}$ a time value that includes both the duration of the target event (approximately $15\mu s$ for a bipolar pulse) as well as the uncertainties in the ToAref calculation and in the receiver positions. The original signals are cropped between $t1$ and $t2$, defined as (see Equations 3,4):

$$t_1 = \mathrm{ToAref} - \mathrm{WS}_{ij} \quad (3)$$

$$t_2 = \mathrm{ToAref} + \mathrm{WS}_{ij} \quad (4)$$

- Detection and $ToAref$: in the context of the experimental setup, one of the receivers is designated as the reference point. The data from this receiver are processed using spectrograms generations and calculating the average power spectral density (PSD) from the target frequency band

(10-60 kHz for a bipolar pulse). The purpose of this calculation is to determine whether a predefined threshold is exceeded, considering the level of noise present in the recording. The result of this calculation is the identification of potential events [7], and the arrival time of these events is used as the reference $ToAref$ see Figure 2. The figure 3 presents an of example the results obtained by applying the described methodology to determine the $DToA$. Raw acoustic data provided by the ITINERIS project [8] were used, containing known signal emissions—specifically, sweep signals with frequencies ranging from 20 to 50 kHz and a duration of 5 ms. Before cross-correlation, the signals were normalized, dividing by their Euclidean norm to ensure that signals with different amplitudes are compared relatively, focusing on the shape of the signals rather than their magnitude, preventing misleadingly high correlations due to amplitude differences, which is helpful in possible noisy environments.

3. ESTIMATION OF THE OPTIMAL DISTANCE BETWEEN RECEIVERS

In the Introduction, we mentioned that the receivers will be arranged to form a tetrahedron. Using the methodology outlined in the previous section, we will conduct simulations to calculate the uncertainties in the reconstruction of the emitter's position and orientation by varying the distance between the receivers, that is, by changing the size of our array. We will start with a theoretical model in which we know both the position of the receivers and the position of a source randomly located but at a distances of 1 km from the array. Then, we will vary the separation of the receivers (while maintaining their distribution), the location of the source, and the source-array distance. Since our model is based on DToAs, accounting for the error introduced by calculating these in estimating the source's position is essential. We will add a random value to the ToAs according to the expected uncertainty to address this. The outcome will provide insight into an optimal receiver separation distance (considering as well construction, transportation, and handling) and without compromising the model's accuracy.

4. APPLICATIONS BEYOND ACOUSTIC NEUTRINO DETECTION

In addition to its primary application in UHE cosmic neutrino detection, the array's sensitivity to acoustic phenomena enables a wider range of applications. It could support research in fields such as geophysical acoustics, marine bioacoustics, and the monitoring of anthropogenic noise, thereby making valuable contributions to various scientific disciplines.

- Marine Biology: Detection of vocalisations from marine mammals and fish populations, contributing to biodiversity assessments and behavioural studies.
- Seismic monitoring: Monitoring underwater earthquakes or volcanic activity by detecting associated acoustic waves. It could also be part of a warning system for marine hazards, such as tsunamis.
- Anthropogenic Noise Studies: Long-term monitoring of anthropogenic noise pollution, such as from shipping or seismic exploration, offshore drilling, use of explosives, low- and mid-frequency active sonar, and its effects on marine ecosystems.

5. CONCLUSIONS AND NEXT STEPS

The proposed design of an acoustic sensor system represents a promising and complementary approach to traditional optical methods for ulta-high energy neutrino detection. The application of multilateration as a method for estimating the unknown position of a source is particularly robust in environments such as marine settings. The applicability of this design can be extended to other fields, such as geophysical acoustics, marine bioacoustics, and anthropogenic noise monitoring. Future work will focus on finalising the design, with special attention to structural and mechanical aspects. We will continue to optimise and validate the system in experimental environments by simulating the acoustic signals produced by the interaction of neutrinos, seismic waves, and marine mammal vocalisations added to real experimental acoustic recordings. This approach aims to improve the accuracy and applicability of the system to experimental acoustic data to improve its accuracy and applicability.

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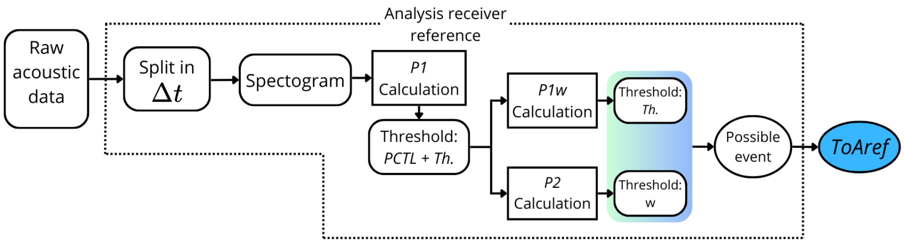

Figure 2: Workflow detection phase and *ToAref*.

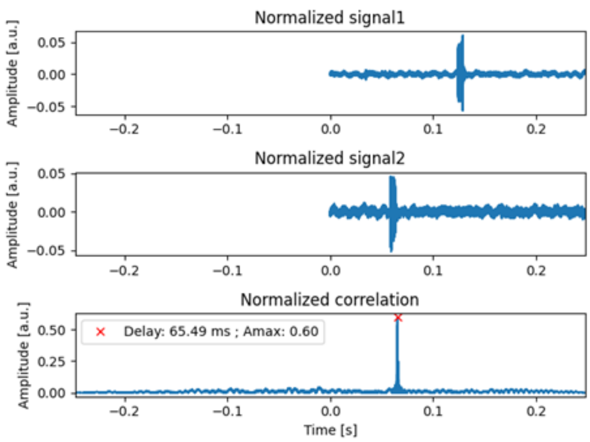

Figure 3: Example signal sweep 40-36 kHz.

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