XIII Congresso Ibérico de Acústica
55º Congreso Español de Acústica
TECNIACÚSTICA 2024
Faro, 11 a 13 setembro 2024
ACÚSTICA 2024
SEA
spa

ACOUSTIC POSITIONING SYSTEM ON KM3NeT NEUTRINO TELESCOPE

Carlos-Alberto Quiroz-Rangel[1], Miguel Ardid[1], Dídac Diego-Tortosa[2]
on behalf of the KM3NeT Collaboration.

[1] Universitat Politècnica de València (UPV-IGIC), Paranimf, 1, Gandia, 46730
carquira@upv.es, mardid@fis.upv.es
[2]Istituto Nazionale di Fisica Nucleare (INFN-LNS), Via S. Sofia, 62, Catania, 9512
didac.diegotortosa@lns.infn.it

Resumen

KM3NeT es una infraestructura de investigación en construcción que consta de dos nodos de detección en el mar Mediterráneo llamados ARCA (Astroparticle Research with Cosmics in the Abyss) instalado a 100 km de la costa de Sicilia (Italia) a una profundidad de 3,5 km, y ORCA (Oscillation Research with Cosmics in the Abyss) instalado a 40 km de la costa de Toulon (Francia) a una profundidad de 2,5 km. Estos detectores se basan en detectar la luz producida tras la interacción de un neutrino con una red de tres dimensiones de Módulos Ópticos Digitales. Para la reconstrucción de la trayectoria y energía de la partícula es necesario conocer la posición relativa de los Módulos Ópticos con buena precisión (~10 cm). Los Módulos Ópticos están en constante movimiento debido a las corrientes marinas; por ello, KM3NeT dispone de un Sistema de Posicionamiento Acústico y un software de procesamiento denominado Filtro de Datos Acústicos. El Filtro de Datos Acústicos cuenta con Balizas Acústicas ancladas en posiciones conocidas del fondo marino. Cada Baliza acústica emite una señal específica. Si los sensores piezocerámicos de los Módulos Ópticos registran estas señales, el Filtro de Datos Acústicos guarda su tiempo de llegada. Actualmente, estos tiempos se calculan mediante una función de correlación cruzada entre los datos acústicos brutos registrados y la señal de referencia. A continuación, estos tiempos de llegada se utilizan para posicionar los receptores acústicos mediante un proceso de optimización de la multilateración. Este manuscrito describe el Sistema de Posicionamiento Acústico de KM3NeT y presenta un estudio comparativo entre el proceso actual del Filtro de Datos Acústicos y los resultados utilizando una función de correlación cruzada normalizada, también utilizando patrones a partir de señales experimentales registradas directamente por los hidrófonos del telescopio.

Palabras clave: Acústica Submarina; Sistema de Posicionamiento Acústico; KM3NeT.

Abstract

KM3NeT is a research infrastructure under construction consisting of two detection nodes at the Mediterranean Sea: ARCA (Astroparticle Research with Cosmics in the Abyss) installed 100 km off the coast of Sicily (Italy) at a depth of approximately 3.5 km, and ORCA (Oscillation Research with Cosmics in the Abyss) installed 40 km off the coast of Toulon (France) at a depth of approximately 2.5 km. ARCA and ORCA are 3D arrays of Digital Optical Modules for detecting the light produced by secondary particles from neutrino interactions. The precise knowledge of the relative positions of the Digital Optical Modules (~10 cm) is mandatory for the reconstruction of the particle trajectory and energy. The Digital Optical Modules are constantly moving due to the sea currents; therefore, an Acoustic Positioning System is employed for monitoring their position. Acoustic Beacons are deployed in known positions on the sea floor. Each Acoustic Beacon emits a specific signal. The Digital Optical Modules are equipped with piezoceramic sensors which record these signals, and their Time of Arrival are saved through the Acoustic Data Filter process. Currently, these Times are found by a cross-correlation function between the recorded acoustic data and the ideal reference signal. Then, these Times of Arrivals are used to position the acoustic receivers by a multilateration optimization process. This manuscript describes the KM3NeT-Acoustic Position System and presents a comparison study between the current Acoustic Data Filter process and the results using a normalized cross-correlation function, also using patterns from experimental signals directly recorded by the telescope's hydrophones.

Keywords: Underwater Acoustics, Acoustic Positioning System, KM3NeT.

PACS no. 43.30.Xm, 43.30.Yj

1. Introduction

KM3NeT (Acronym for Cubic Kilometer Neutrino Telescope) [1] is a research infrastructure installing two neutrino detectors in the Mediterranean Sea ARCA (Astroparticle Research with Cosmic in the Abyss) at 100 km off the coast of Sicily (Italy) at a depth of ~3.5 km for neutrino astronomy and ORCA (Oscillation Research with Cosmic in the Abyss) 40 km off the coast of Toulon (France) at a depth of ~2.5 km for studying the fundamental properties of neutrinos. The first ARCA detection line or detection unit (DU) was installed in 2015; 28 lines are currently operational and taking data. The first ORCA detection unit was installed in 2017; 19 lines are presently operational. When the construction is completed, ARCA will host 230 detection units and ORCA 115 detection units.

Each DU consists of a base anchored to the seabed, a buoy that keeps the line taut, and 18 DOMs [2] arranged along the line. The DOMs are equipped with photomultipliers. The optical modules used in the ARCA and ORCA detectors feature an innovative design. Unlike traditional neutrino telescopes that use a single large photomultiplier tube (PMT) enclosed in a glass sphere, the KM3NeT DOMs incorporate 31 small PMTs. Additionally, they house calibration devices and the complete front-end and readout electronics. The vertical distance between DOMs and the horizontal distance between DUs differs for the two detectors. In ORCA the distance between DUs is approx. 20m and the vertical distances between DOMs approx. 9m, whereas in ARCA the distance between DUs is approx. 90m and vertical distances between DOMs approx. 36m [1]. The Section 2 are described the APS, its components and instrumentation as well as the data analysis procedure. The current configuration of the APS is reviewed and discussed in Section 3. In Section 4 the results are presented obtained from simulations of the current configuration and methodology, as well as the study conducted using different signals and techniques in signal analysis. The conclusions are summarized in Section 5 and in Section 6 a list of the next steps is included.

(a) (b)

Figure 1: (a) ARCA and ORCA final configurations. (b) A KM3NeT-DU and a KM3NeT DOM.

2. The Acoustic Positioning System (APS)

The detection principle and technology are the same for both telescopes: the trajectories of charged particles produced by neutrino interactions are reconstructed through the detection of the Cherenkov light. The detection principle of the KM3NeT telescopes is illustrated in Fig.2 (figure 2) for the case of a muon resulting from a neutrino interaction with matter below the sea bed. The Cherenkov light cone emitted along the muon trajectory is depicted. The neutrino's direction is reconstructed from the arrival times of the Cherenkov light at the optical modules and the positions of these modules.

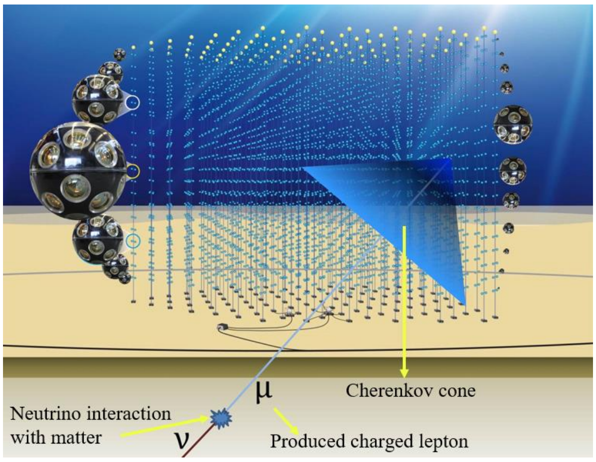
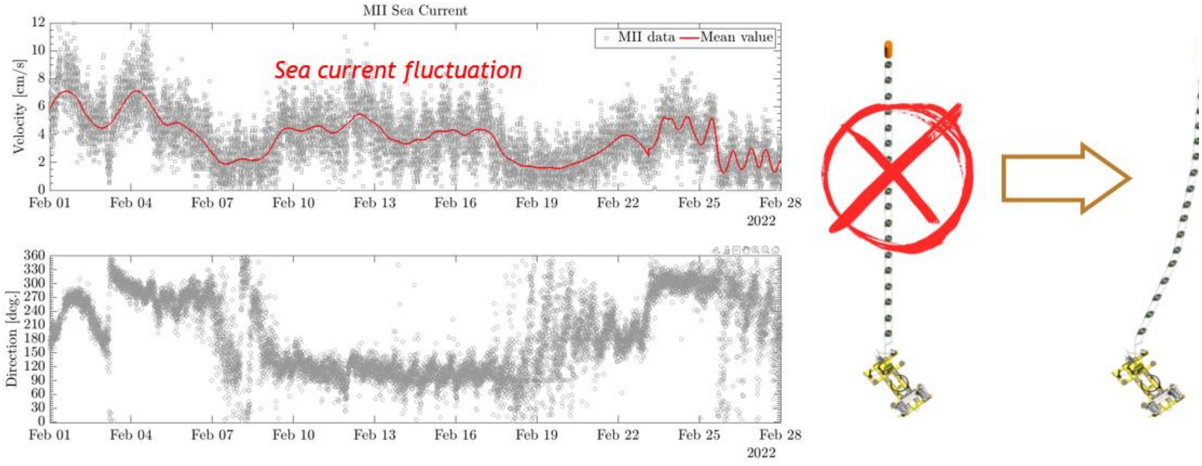


Figure 2: Illustration of the detection principle of the KM3NeT telescopes.

Sea currents produce movements of the DOMs (see figure 3). Knowing the exact position of the detectors at the time an interaction is recorded is necessary to determine the neutrino trajectory. The positioning system consists of an acoustic positioning system (APS) that monitors the position of DOMs, and additional system that determines the DOM orientation.



(a) (b)

Figure 3: (a) Experimental sea current data in ORCA [4]. (b) Illustration of the sea current effect on a DU [4].

The APS consists of transmitters called Acoustic Beacons (AB) anchored to the seafloor in known fixed positions and Digital Acoustic Receivers (DARs) in the DU, (see figure 4). The DARs are of two types: internal piezoceramic sensors, inside each DOM, and external hydrophones fixed at the base of each DU. The recording of acoustic signals captured by the receivers makes also possible to perform acoustic studies of the environment, such as environmental noise evaluations, bioacoustics studies, and neutrino acoustic detection, among others.

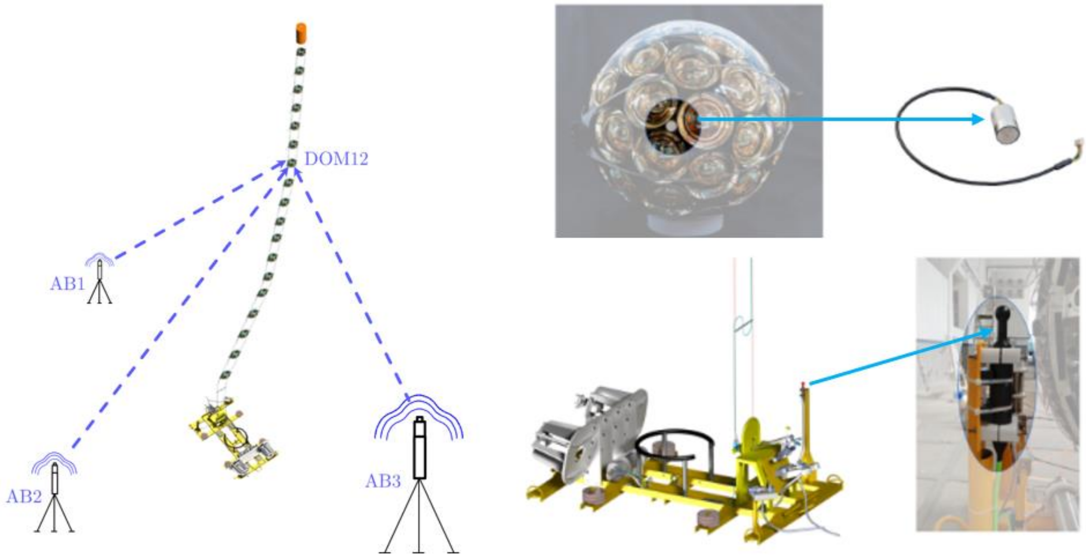


Figure 4: Schematic view of the APS with a zoom to the DARs in the right part.

The primary goal of the Acoustic Data Filter (ADF) is to identify emissions from the acoustic positioning system and determine the arrival times of these signals. The ToA of the acoustic signals detected by the DARs is measured by analyzing its data flow. A Long Baseline (LBL) positioning system is an underwater navigation method that relies on distance measurements to fixed, calibrated transponders installed on the seabed. Once an LBL-beacon pulse is identified, it is associated with the detector’s absolute GPS time (Unix time stamp). The distance between each beacon and DAR is then calculated, considering the acoustic signal's Time of Emission (ToE) and the sound velocity (SVP) along the water column. By knowing the locations of the LBL beacons, the position of each DAR can be calculated onshore by a pc farm using algorithms based on spherical multi-lateration [3].

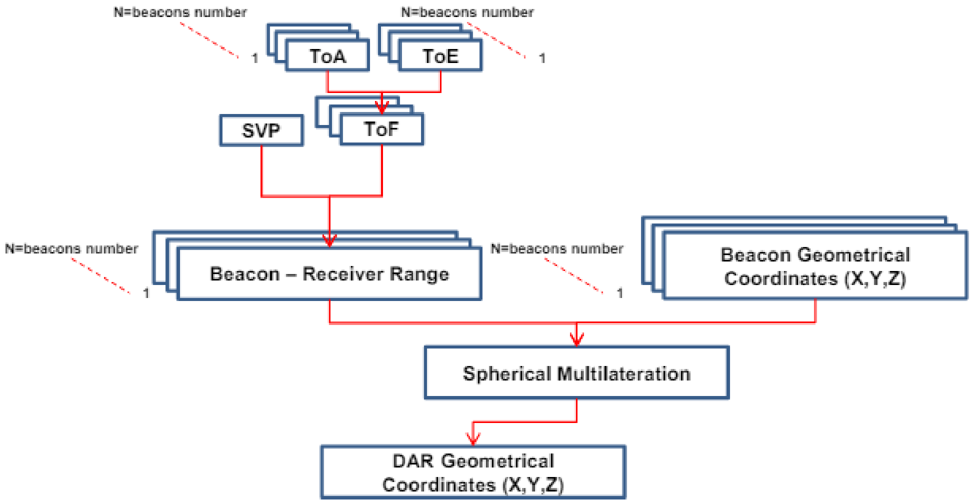


Figure 5: Schematic view of the DOM positioning software.

The cross-correlation function between the acoustic data flow and the reference signals of all the emitters is done to identify the emitter signals and determine the ToA. These cross-correlation results show a prominent peak or Quality Factor (QF) where the similarity between the expected and recorded signals is greatest. By comparing the magnitude of this peak with results from other emitters and the spatial-temporal correlations between DARs, the specific emitter can be identified, and the Time of Emission (ToE) of the corresponding emitter can be determined. The sound speed gradient (c_{sound}) is estimated based on environmental properties (with c_{sound} ranging from 1552.0 to 1563.8 m/s in ARCA and 1545.6 to 1549.0 m/s in ORCA) and using the ToA and ToE values the Time of Flight (ToF) can be calculated, allowing for determining the distance. Using all emitters triangulation can be performed to obtain the x, y, and z coordinates of each receiver.

3. Status:

Acoustic signals propagate effectively through water. For instance, a 32 kHz tone emitted at a pressure level of 180 dB re 1 µPa at 1 meter will have a signal amplitude of approximately 110 dB re 1 µPa at 2 km. [3].

In the preliminary phases of telescope construction, with less than 30 (ARCA) / 20 (ORCA) DUs and an LBL configuration with no more than 4 ABs, the ADF effectively distinguishes the correct emitters. However, as the number of deployed DUs increases, the distance between APS elements grows, and the number of ABs increases, the assignment of the received signal to the right AB becomes more complicated. There may be cases in which the highest QF calculated does not correspond to the correct emitter but to a closer emitter due to the influence of the amplitude of the received signal on the correlation values. Alternatively, the saturation effect on the received signal occurs when the transmitter-receiver distance is small. This situation makes necessary to seek for improvements in the analysis performed by the ADF to ensure accuracy in identifying the emitters. On the other hand, the use of small-time windows generates a high ratio of QFs and ToAs which leads to excess data and memory usage in the database.

4. Results:

The ADF generates and stores a list of theoretical sinusoidal reference signals as sweeps in the frequency range from 20 to 40 kHz y 5ms duration (see figure 6).

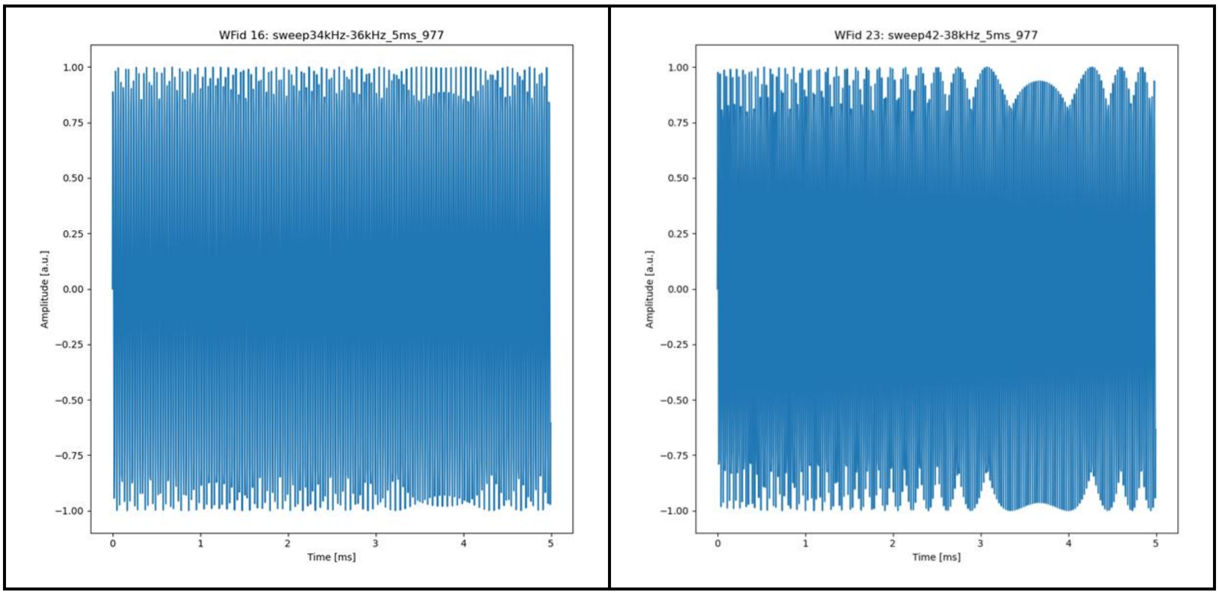


Figure 6: Example of reference signals generated by ADF.

The ABs generate and emit the same type of signals that are subsequently recorded by the hydrophones installed on some DU and the piezo installed on all DOMs (see figure 7). Differences in the signals may arise from the varying response characteristics of the receiver, as well as differences in the propagation distance and the angle between emission and reception.

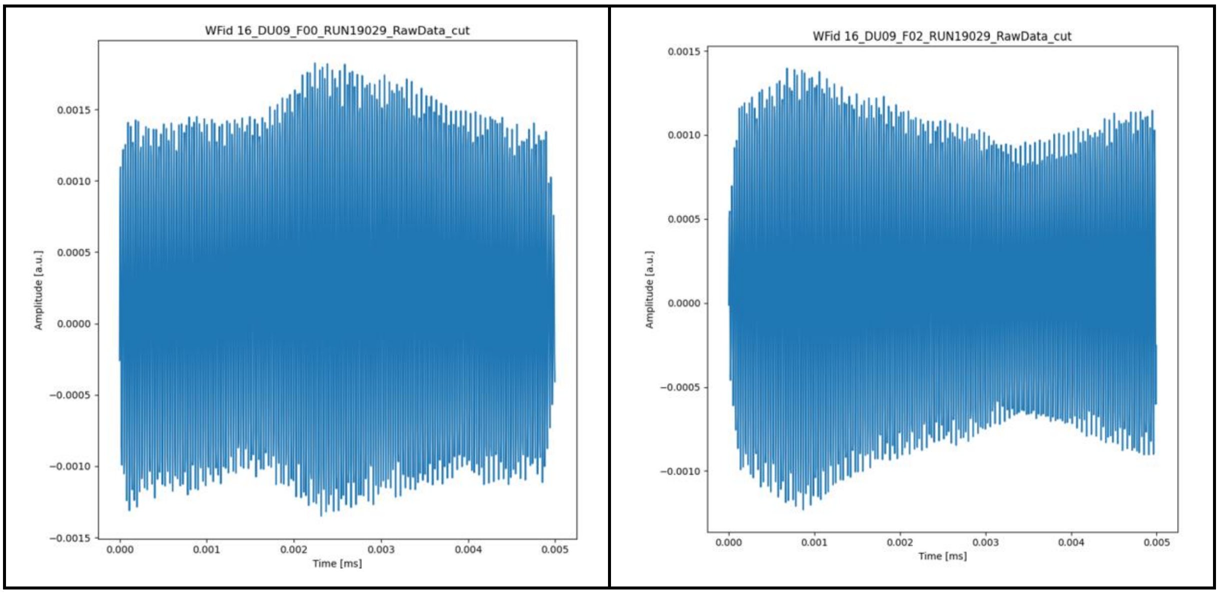


Figure 7: Example of signals emitted by ABs recorded by hydrophone (left) and piezo (right).

This work uses the data recorded by the detector, which at the time had a configuration of 4 emitters (one at the base of a DU and 3 so-called autonomous) and the recordings from a hydrophone and 18 piezo of the same DU. The first approach of this work is to use the *“normalized”* cross-correlation to calculate the QF and ToA, dividing the recorded and reference signals (WFs) by their Euclidean norm (L2) [Equation 1] before correlating them.

$$L_2 = ||x||_2 = \sqrt{\sum_{n=0}^{N-1} |x[n]|^2} \quad and \quad x_{normalized} = \frac{x}{||x||_2} \tag{1}$$

Where $x[n]$ is the signal (reference or stored in the DB).

The two cross-correlation methods (cross-correlation and normalized cross-correlations) of a 40 kHz to 36 kHz sweep signal of 5 ms duration recorded on the hydrophone versus the same sweep (reference) are shown in Fig 8 (see figure 8). The normalized cross-correlation is not affected by the signal level, which makes it easier to distinguish the correct expected signal.

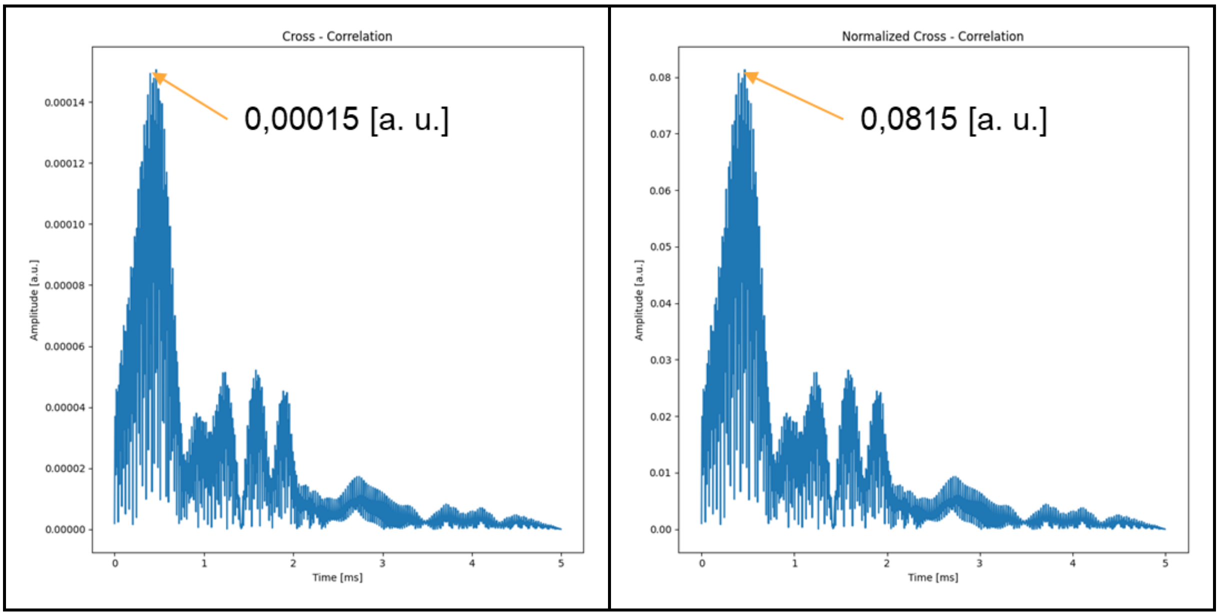


Figure 8: Cross- correlation (left) Normalized Cross - Correlation (right).

The results are presented in Fig. 9 (see figure 9) in the form of a correlation matrix, comparing the values with some waveforms (described in table 1 (see Table 1)) used by the telescope and show that using a normalized correlation, the values for the right signal are higher with respect to the uncorrect WF patterns, therefore facilitating the discrimination and the selection of the correct ToA. It is presented for the case of hydrophones; for piezo sensors in the DOMs, a similar result is obtained.

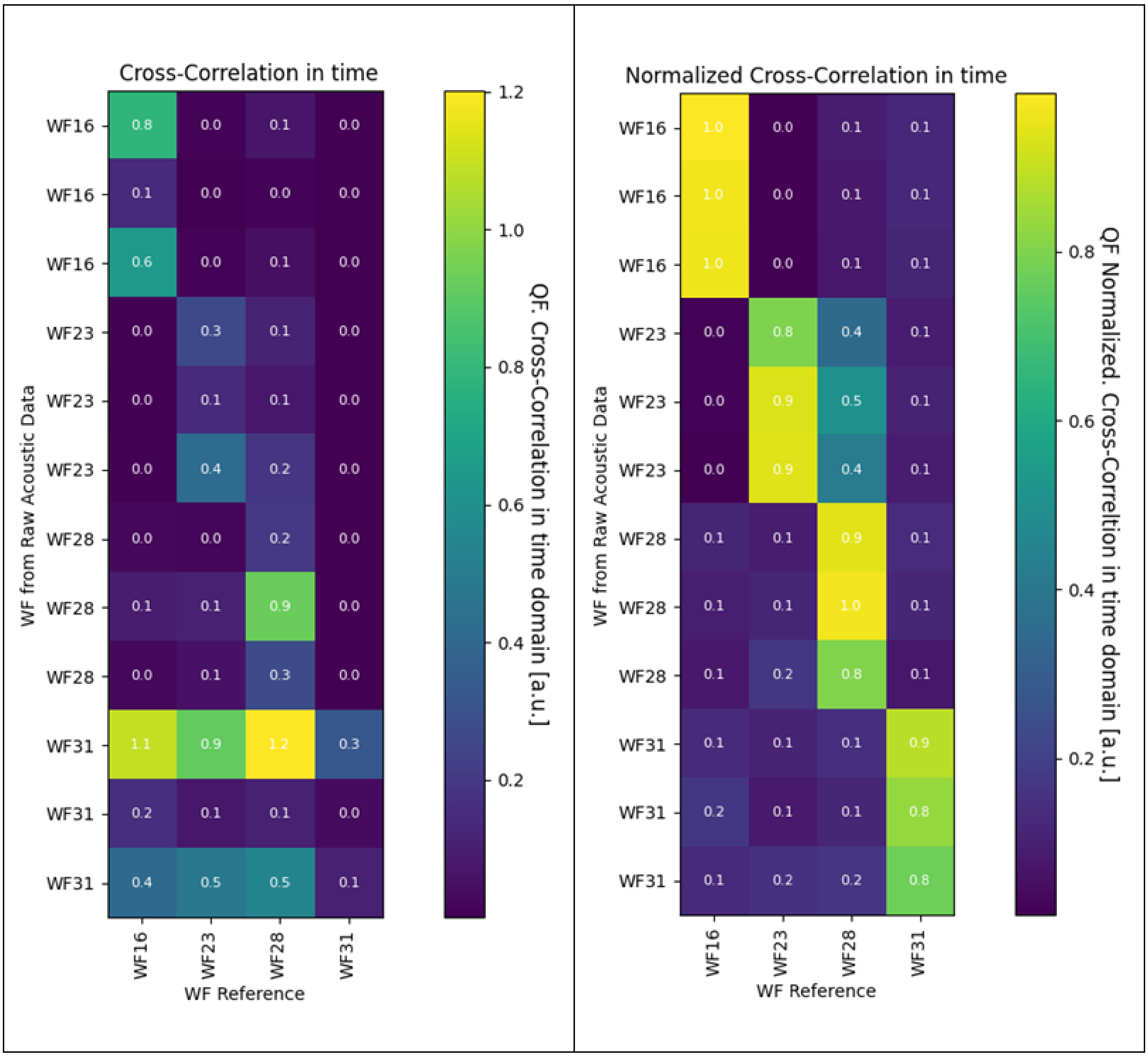


Figure 9: Cross- correlation (left) Normalized Cross - Correlation (right).

Waveform	signal
WF16	Sweep 34 kHz - 36 kHz
WF23	Sweep 42 kHz - 38 kHz
WF28	Sweep 40 kHz - 36 kHz
WF31	Sweep 20 kHz - 40 kHz

Table 1: Description waveform pattern.

Continuing with the use of *"normalized"* cross-correlation, the next scenario involves using signals derived directly from the raw data as the reference signal (WF); specifically, 40 kHz to 36 kHz sweep signal recorded with hydrophone. No significant effect or clear improvement is observed on the QF value using this WFs (see figure 10).

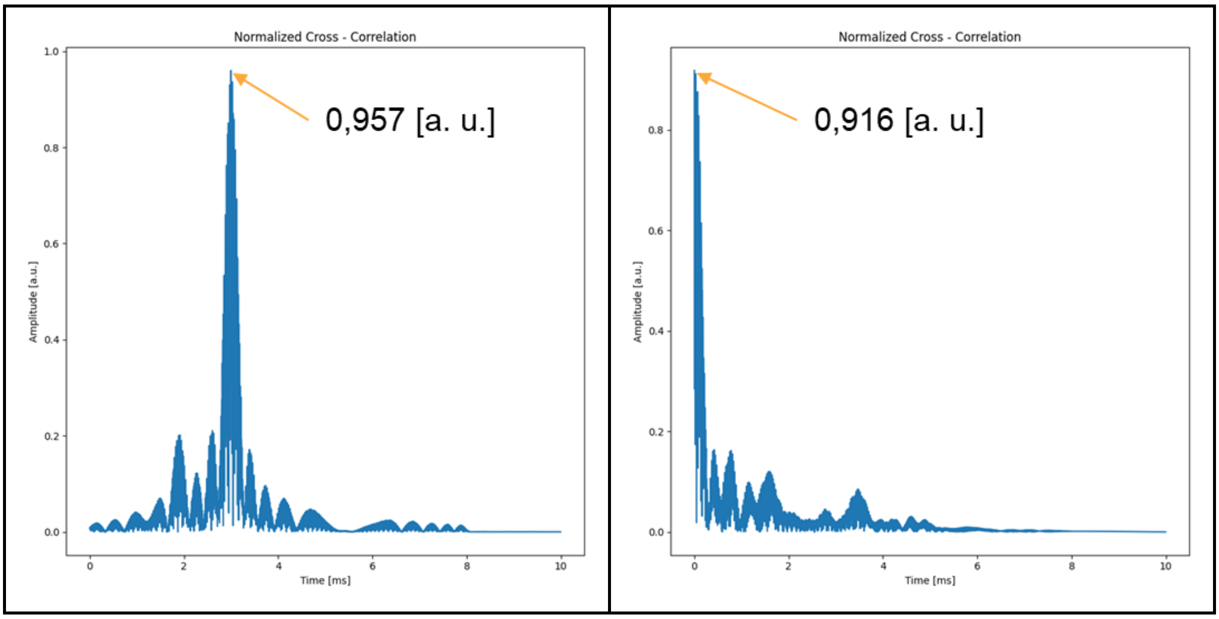


Figure 10: Normalized Cross- corr. WF reference DB (left) Normalized Cross- corr. WF reference recorded (right).

5. Conclusions and next steps

The main aspects of the APS of KM3NeT have been presented, focusing on the work for improving the processing of the acoustic data. An optimization of the ADF workflow is considered to maintain the good performance as the size of the telescope increases. Memory usage can be managed by adjusting the size of the time window when calculating the ToAs. Additionally, using *"normalized"* cross-correlation helps distinguishing the QF associated with the correct WF. The difference in the correlation value when using signals recorded by hydrophones or piezo as references is negligible compared to using theoretical signals. The presented workflow can serve as a test bench for studying other waveforms that may be used as reference signals in the future. When defining the waveform to be emitted by nearby AB, it is crucial to ensure that their respective bandwidths do not overlap; this avoids generating QF values of similar sizes, which could lead to errors in ToA selection.

Next, we are willing to quantify the effect of changing the time window size at the time of correlation calculation, to optimize the design of WFs using the correlation matrix and additional information such as the duration, bandwidth, emission ratio, etc. We plan to quantify the effects of distance and angle of incidence between emitters and receivers on QF-values. Also, the absorption and refraction effects and the different directivity and sensitivity patterns of emitters and receivers may be considered. This comprehensive approach ensures a thorough analysis of the subject.

References

[1] Adrián-Martínez, S., Ageron, M., Aharonian, F., Aiello, S., Albert, A., Ameli, F., Anassontzis, E., Andre, M., Androulakis, G., Anghinolfi, M., Anton, G., Ardid, M., Avgitas, T., Barbarino, G., Barbarito, E., Baret, B., Barrios-Martí, J., Belhorma, B., Belias, A., ... Zúñiga, J. (2016). Letter of intent for KM3NeT 2.0. *Journal of physics. G, Nuclear and particle physics: an Institute of Physics journal*, 43(8), 084001. https://doi.org/10.1088/0954-3899/43/8/084001.

[2] Collaboration, Km. (2022, March 18). The KM3NeT multi-PMT optical module. ArXiv.org. https://arxiv.org/abs/2203.10048

[3] Viola, S., M. Ardid, V. Bertín, Lahmann, R., Pellegrino, C., Riccobene, G., M. Saldaña, Sapienza, P., & Simeone, F. (2016). Acoustic positioning system for KM3NeT. Proceedings of the 34th International Cosmic Ray Conference — PoS(ICRC2015). https://doi.org/10.22323/1.236.1169

[4] Diego Tortosa, D. (2022, October 28). Positioning System and Acoustic Studies for the KM3NeT deep-sea neutrino telescope. Riunet.upv.es. http://hdl.handle.net/10251/188917.