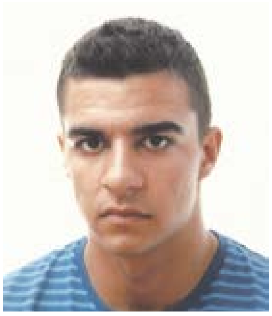
Underwater acoustic positioning system for the monitoring of KM3NeT optical modules[1]



Ardid, M.[1]; Bou-Cabo, M.[2]; D.Tortosa, D.[1]; Martínez-Mora, J.A.[1]; Poirè, C.[1] for the KM3NeT Collaboration

[1] Institut d'Investigació per a la Gestió Integrada de les Zones Costaneres (IGIC) – Universitat Politècnica de València (UPV), España

[2] Instituto Español de Oceanografía (IEO). Mixed unit UPV-IEO, Valencia,España

didieit@upv.es

PACS: 43.60.Bf

Premio Andrés Lara para jóvenes investigadores 2019

I-INCE Classification of Subject Number: 20

Resumen

KM3NeT, el detector submarino que se encuentra en construcción en el Mar Mediterráneo, usa Módulos Digitales Ópticos (DOMs) para localizar neutrinos, a través de la detección de la luz de Cherenkov producida por partículas relativistas durante la interacción con el agua. Para reconstruir el camino seguido por el neutrino, es necesario saber la posición de cada DOM, el cuál no se encuentra fijo ya que está sujeto a unos cables anclados que se mantienen en vertical gracias a una boya en el final de la línea, lo cual la hace sensible al movimiento de las corrientes marinas. Cada DOM contiene instalada una cerámica piezoeléctrica, como receptor acústico, y usando unos emisores anclados en el fondo del mar se puede estimar la posición de cada DOM triangulando las distancias entre ellos, las cuales se saben por el tiempo de vuelo de la señal acústica. En este trabajo, se presenta una simulación del sistema y se describe el modelo acústico usado.

Palabras clave: Acústica Submarina, Detección Acústica, Simulación, KM3NeT.

Abstract

KM3NeT, the underwater neutrino telescope in the Mediterranean Sea, is a detector under construction. KM3NeT uses Digital Optical Modules (DOMs) to detect neutrinos by detecting the Cherenkov light of relativistic particles produced in the interaction. To reconstruct the neutrino event and the coming direction, it is necessary to monitor the position of each DOM, which is not fixed since it is mounted in flexible string lines, held close to vertical by buoys but sensitive to sea currents. A piezo-ceramic transducer is installed inside of each DOM. Using some emitters anchored in the sea floor it is possible to calculate the position of the DOMs by triangulation of distances obtained from the determination of the time of flight of the acoustic wave. In this work, the acoustic model used for the simulation of the system is described and the results presented.

Keywords: Underwater Acoustics, Acoustic Detection, Simulation, KM3NeT.

1. Introduction

KM3NeT [1], which is now under construction, will be the biggest underwater neutrino detector in the world. It is located in the Mediterranean Sea and will use thousands of Digital Optical Modules (DOMs) arranged in vertical structures, called Detection Units (DUs), each one with 18 DOMs. This will form a 3D array of optical sensors to detect neutrinos through the Cherenkov light emitted by the relativistic particles produced in the interaction. KM3NeT comprises two nodes: ORCA, devoted mainly to the studies of neutrino oscillations and the determination of the mass hierarchy of neutrinos, and ARCA devoted mainly to high-energy neutrino astronomy. ORCA, located 40 km offshore *Toulon* at 2500 m of depth, will have a more compact structure with 115 DUs

[1] Artículo publicado en inglés por haber sido presentado y premiado en INTER-NOISE 2019.

distributed in 0.018 km^3. ARCA, located 100 km to *Porto di Capo Passero* at 3500 m of depth, will consist of two blocks of 115 DUs distributed in ~1 km^3 (see *Figure 1*). In phase-1 of KM3NeT, the plan is to build and install the first 7 DUs in ORCA and the first 24 DUs in ARCA.

As shown in *Figure 1.a*, the DUs are anchored on the seabed and the DOMs are distributed along a flexible string kept almost vertical by a buoy on top. The DU is then sensitive to the sea current and DOMs are not in fixed positions but can have displacements of several meters from their nominal positions. Considering that the particle trajectories are reconstructed rom correlations of the arrival times of Cherenkov photons on the DOM, the position of the DOMs must be known with ~10 cm accuracy. KM3NeT has therefore implemented an Acoustic Positioning System (APS) [2], including a piezoceramic inside each DOM, with the function of receiver, and a hydrophone at the base of each DU. Furthermore, an array of Acoustic Beacons (ABs) is installed in fixed positions on the Sea bottom. The principle is to detect the signal emitted by the ABs by each DOM and apply a triangulation method to determine the DOM position, similarly to the predecessor ANTARES neutrino detector [3].

The purpose of this paper is to study, for the first phase of ORCA with a few autonomous ABs, the reliability and precision of the triangulation through acoustic positioning of each DOM and the DU line fit model to determine the shape of the DU.

2. Simulation method

In the deployment of the DUs and ABs on the seabed it is difficult to measure their position with high precision. To deal with these uncertainties, in the present study a 1 m uncertainty in the location of these items (coordinates *x*, *y* and *z*) is considered.

2.1. Mechanical prediction

The mechanical model considers buoyancy and the drag force of each item in the DU to determine the shape of the DU for a given sea current velocity, in a similar way as done in ANTARES [4]. From the value of the speed and direction of sea current, it is possible to estimate the position of DOMs in the DU.

In this study, the mechanical model is used to indicate the "initial position" for each receiver. During this test study the velocity of sea current is taken as 55 mm/s and the direction as 45º from the North (this is an experimental data in ORCA for a random day, but they are common values). The relative displacement of the DOMs between the vertical of DU baseline is shown in *Figure 2.a* and the "initial position" of the simulation in *Figure 2.b*.

2.2. Acoustic simulation

The simulation of the acoustic part of this study is done by the detection of signals received by each DOM (piezos) and DU baseline (hydrophones) emitted by the autonomous ABs.

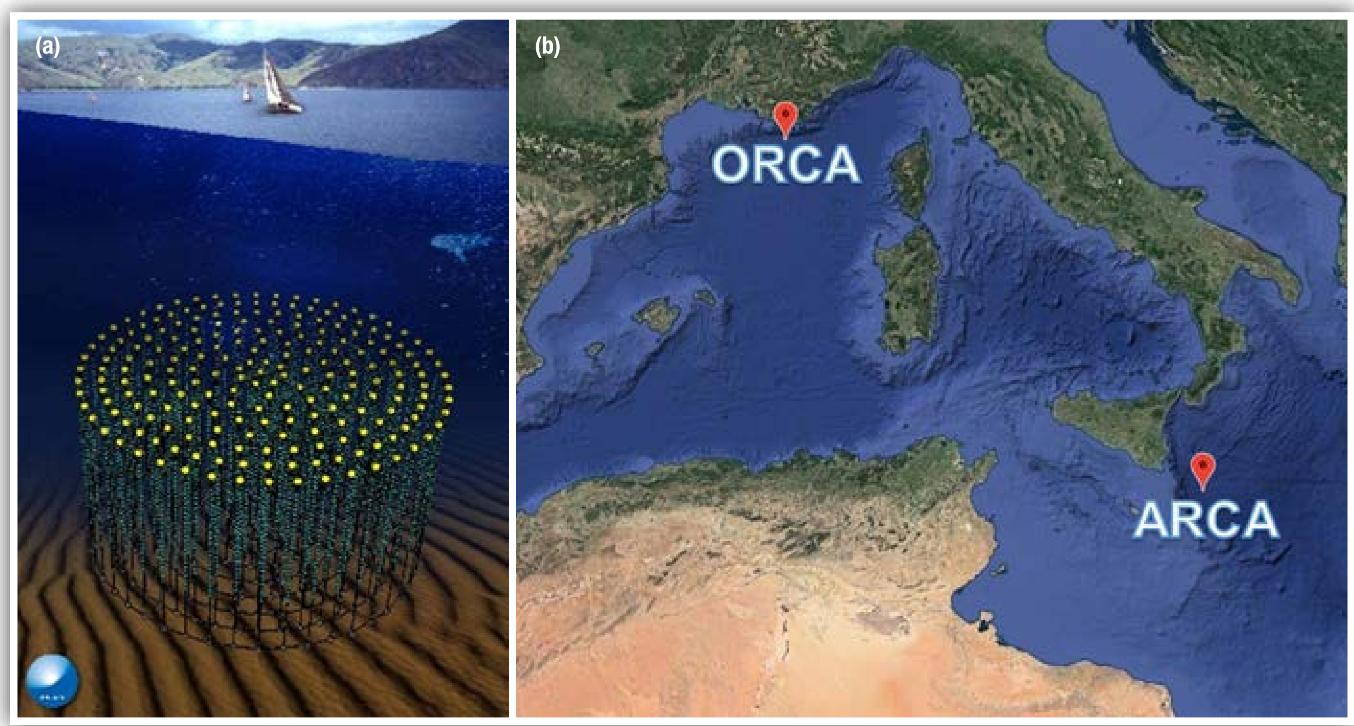


Figure 1. (a) Schematic view of one infrastructure of KM3NeT. **(b)** Location of two sites in KM3NeT detectors.

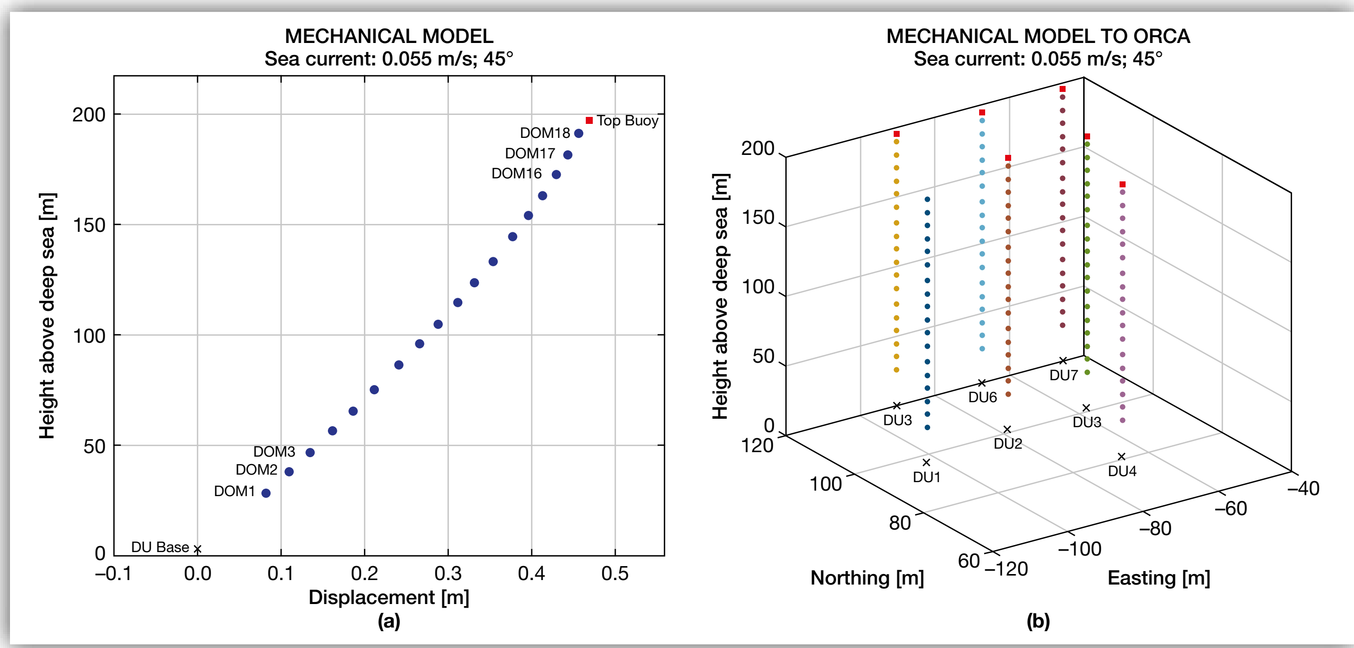


Figure 2. Mechanical model's prediction for 55 mm/s at 45º of sea current. (a) Displacement from vertical. (b) Positions for all lines.

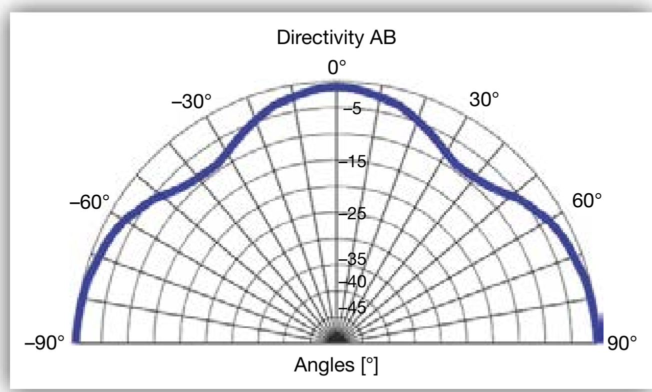


Figure 3. Directivity diagram of AB.

The Source Pressure Level (SPL) of an AB is 180 dB (re 1μPa @1m) and the directivity is considered in the simulation system (see *Figure 3*).

The signal emitted by each AB is a sweep signal of 5 ms with different frequency range (see *Figure 4*): from 26 to 28 kHz for AB1, from 30 to 32 kHz for AB2, and from 34 to 36 kHz for AB3

With respect to the propagation of signals, the spherical divergence and the *François & Garrison's model* for absorption is considered, using the *Medwin's equation* to calculate the sound velocity in ORCA [5]. The distance between emitter and receiver (), is calculated from the time

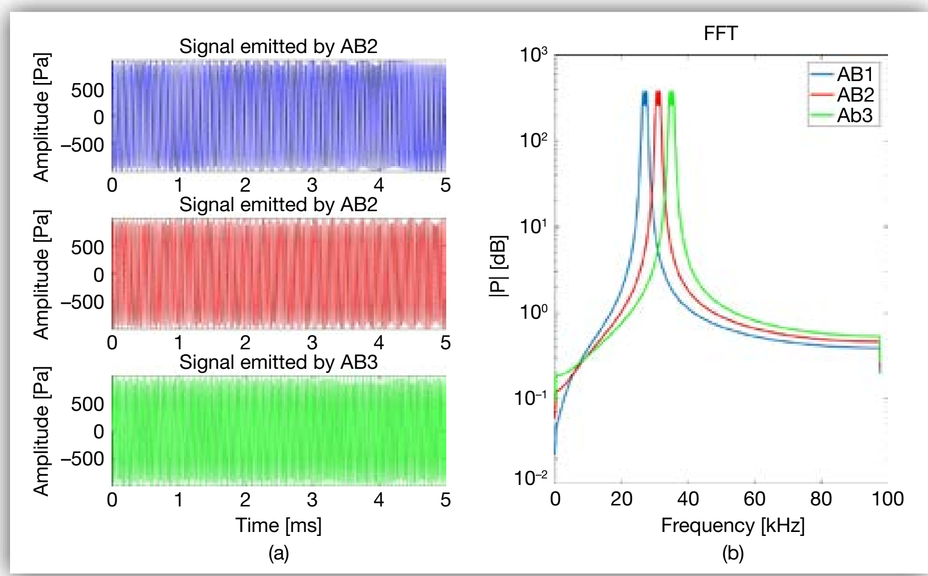


Figure 4. Signals emitted by each AB in time domain (a) and frequency domain (b).

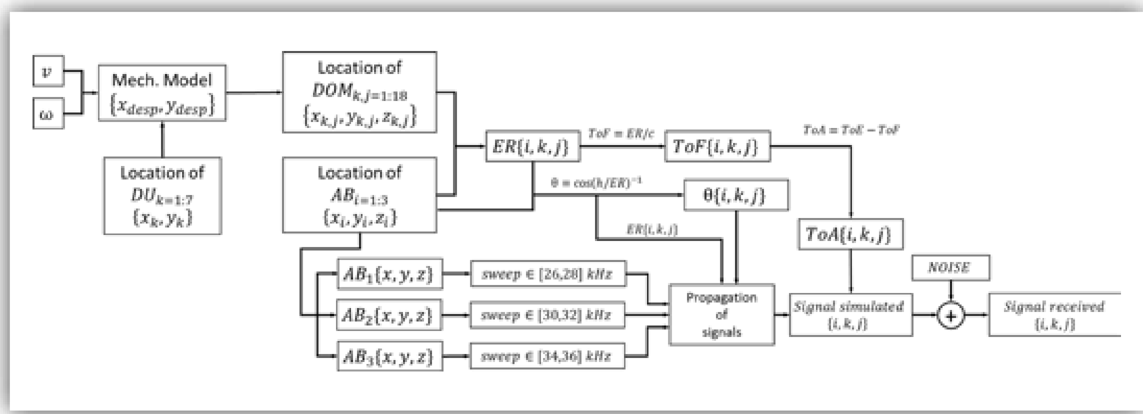


Figure 5. Block diagram for the simulation of the signal received.

of flight of the signal taking into account the Received Voltage Response (RVR) of the piezos in the DOMs.

In summary, the simulation with the value of velocity (υ) and direction (θ) of the sea current and using the mechanical model computes a displacement in *x* and *y* direction, which depends on the floor where the DOM is positioned. Knowing the position of the AB, the algorithm calculates the distance *ER*, consequently the ToF and the angle formed between the AB and the DOM (θ), to consider the directivity of emitter in the emission. The signal received by each DOM is the signal simulated with an experimental noise from ORCA added (see *Figure 5*). The experimental noise, in this occasion, is from a raw acoustic data in a random day with common conditions in the environment.

2.2.1. Validation of the simulation

The validation of the system has been performed using ORCA acoustic data in a period where only a DU and an AB were operative (see *Figure 6*).

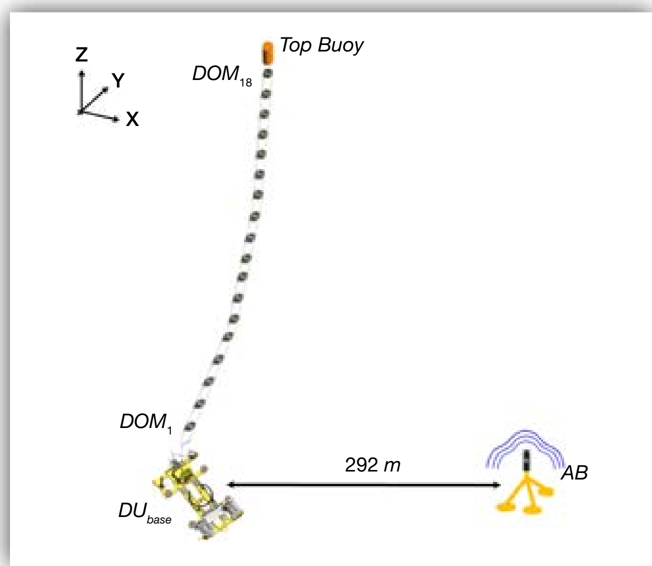


Figure 6. Configuration for validation.

In this case, the acoustic signal emitted by the AB is a sine wave of 32 kHz during 5 ms every 5 min.

To validate the simulation of this work, the signals received in the simulation study is incorporated to a signal received in the real system.

The piezoceramic receiver installed in the DOMs has a Receiving Voltage Response (RVR) of approximately -160 ± 6 dB re μPa/V in the relevant frequency range.

By looking at some experimental signals received in each DOM some differences in the amplitude are observed (*Figure 7*). The amplitude measured in DOMs at a large height of the DU (for example, DOM10 or DOM15, at 115 m and 163 m respectively) is bigger than other ones at low height (for example, DOM1 at 28 m). The difference of the measured amplitude is more than 4 mV, and cannot be attributed to the distance, but it must be related to the directivity response of the receiver or to differences in the manufacturing of the piezos

However, the main aspect in this study is not the amplitude, but the signal detection and the determination of the Time of Arrival (ToA) of the pulses measured accurately, which is usually the case for positive Signal-to-Noise Ratio (SNR) [6].

2.2.2. Acoustic detection and positioning

For the analysis, the signal received in each DOM is filtered by a Band-Pass (PB) FIR filter that uses a Hamming window. The order of the filter is 200, this value does not saturate the signal and has a high quality factor Q (*Figure 8*).

The filter is necessary in case that some signals are received at the same time and are mixed because the cross correlation in time with close sweep signals can be wrong (see *Figure 9*). Then, these filtered signals are studied with a **detector of ToAs** that uses a correlation method in time domain [6].

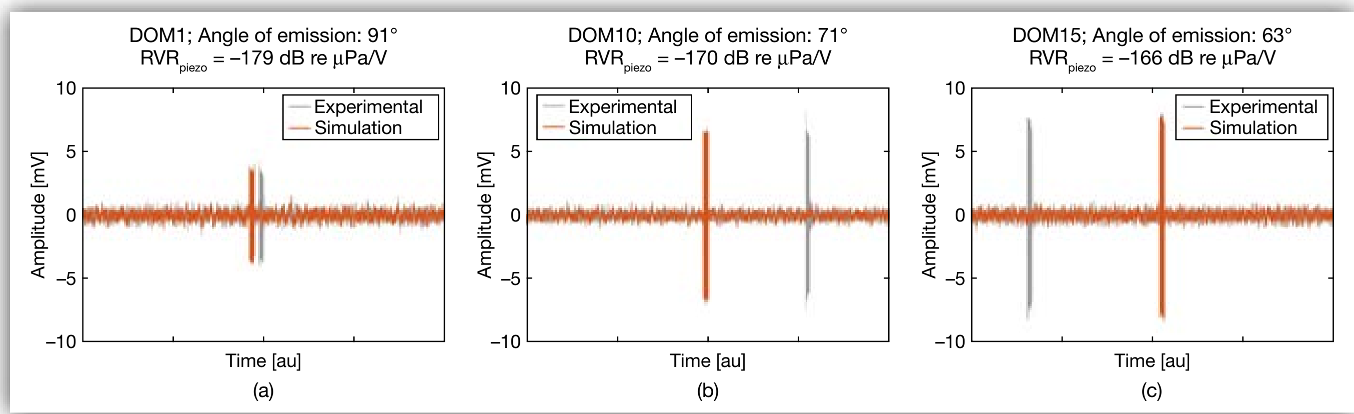


Figure 7. Signal received in arbitrary unit of time (*x* axis) in DOM1(a), DOM10(b) and DOM15(c).

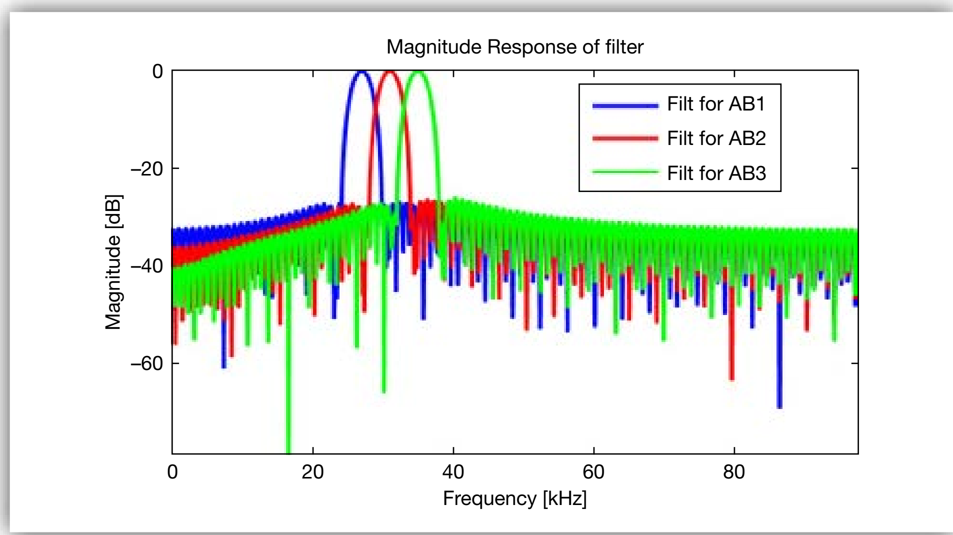


Figure 8. Filters used.

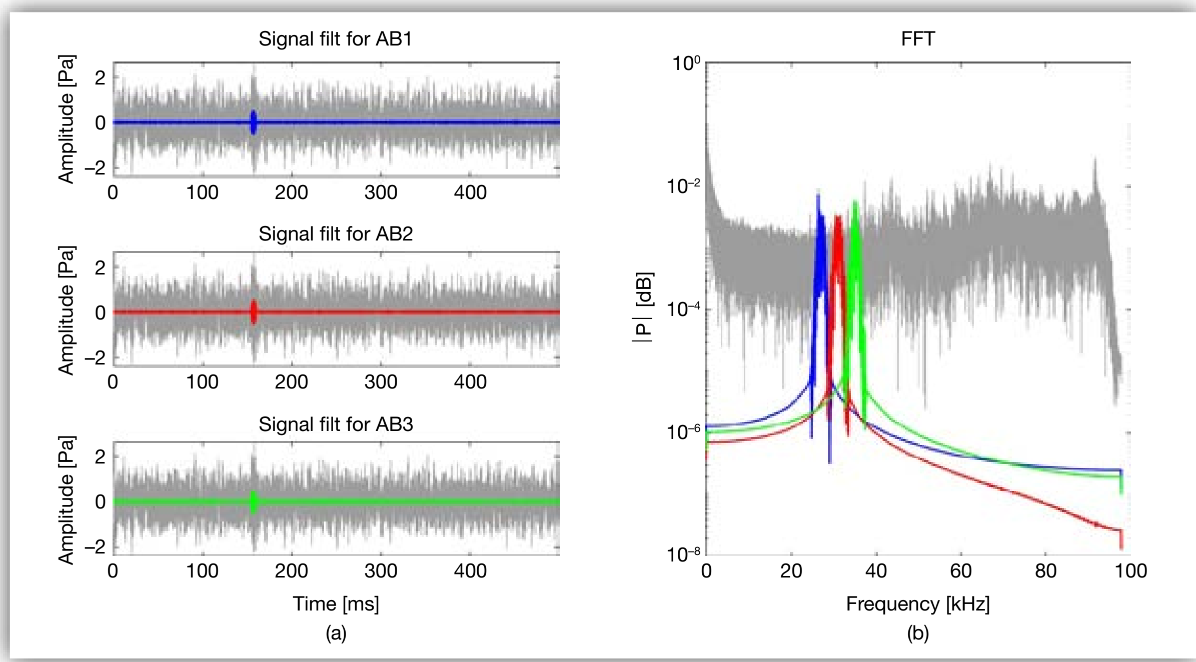


Figure 9. Signal received in DU2-DOM18 filtered to distinguish the signal from AB1, AB2 and AB3.

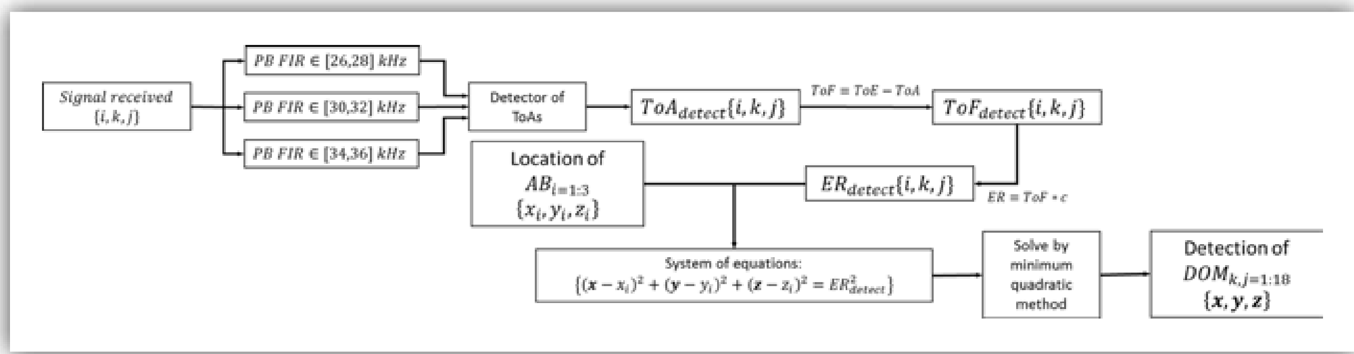


Figure 10. Block diagram for the positioning of receivers.

If the the ToE is known the calculation of the Time of Flight (ToF) is direct and consequently the distance *ER* can easily be estimated provided that the speed of sound is known. Knowing the location of each AB and the *ER*, the simulation can create a system of equations with an equation per emitter (triangulation method). This system of equations is solved by minimisation of residuals to locate each DOM in the *x*, *y* and *z* coordinates (see *Figure 10*). This procedure is used for the simulation studies for ORCA-Phase1 (see *Figure 11*).

2.3. Triangulation method

The DUs in absence of sea current are completely vertical, but with sea current the position of the DOMs change, especially for the transverse *x* and *y* components. The simulation considers that the *z* coordinate -the height- is practically the same independently of sea current since the transverse motion is much smaller than the height. The mechanical model predicts that in a critical situation with high velocity of sea current (20 cm/s), the maximum difference in *z* coordinate is less than 10 cm, but in a common sea current velocity (55 mm/s) this maximum difference is less than 0.55 cm. This consideration moves the 3D problem to a 2D problem (see *Figure 12*).

Given the position of AB, it is possible to know the variable *ER* and consequently its projection on the seabed (*ER*'), following Pythagoras's theorem (*Eq. 1*).

If there are three ABs, it is possible, then, to apply the triangulation (see *Figure 13*) to create the system of equations and resolve it to obtain the position of the receiver.

$$ER' = \sqrt{ER^2 - z_j^2} \qquad \text{Eq. 1}$$

In case of three emitters, there are three equations. The unknown factors in each equation are the position coordinates of receivers. Minimization techniques are used to solve the system.

2.3.1. Uncertainty in measures and analysis

As already said, in the simulation we assume 1 meter for the uncertainty in the locations of ABs and DUs,

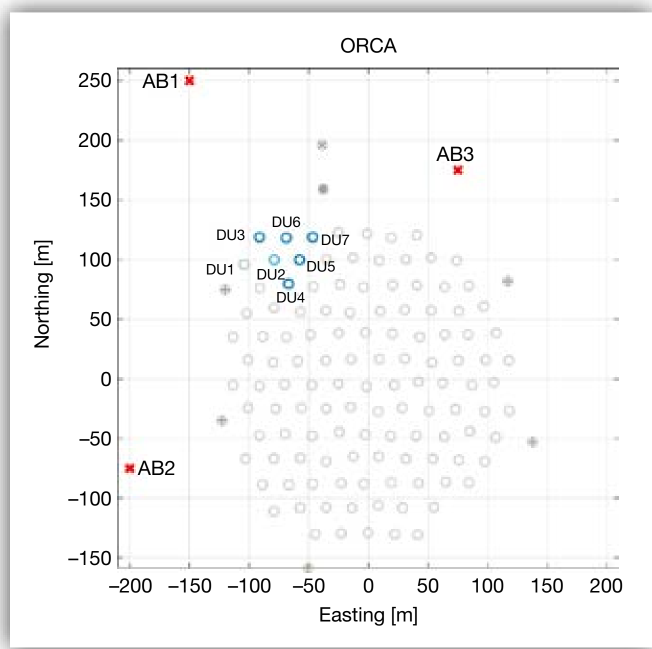


Figure 11. ORCA-Phase1 map.

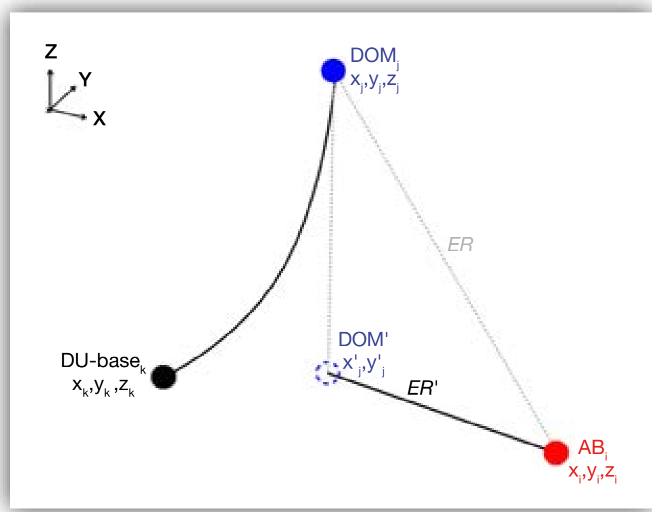


Figure 12. Projection of the distance *ER*.

permitting study the stability of the system to positioning each DOM. The application of this method is shown in *Figure 14* and *Figure 15*.

Since we have a large uncertainty in the AB and DU positions and synchronization is not assured using autonomous beacon, it is better to work with relative distances than absolute ones, so some of the unknowns are cancelled. In this sense, in the analysis three difference position values are calculated:

- Difference 1 (***diff*1**): the difference between the position of the DU baseline and the different DOMs in the DU.
- Difference 2 (***diff*2**): the difference between the position of the DU1 and the position of another DUs.
- Difference 3 (***diff*3**): the difference between the positions of DOMs in the same floor for different DUs (for all lines).

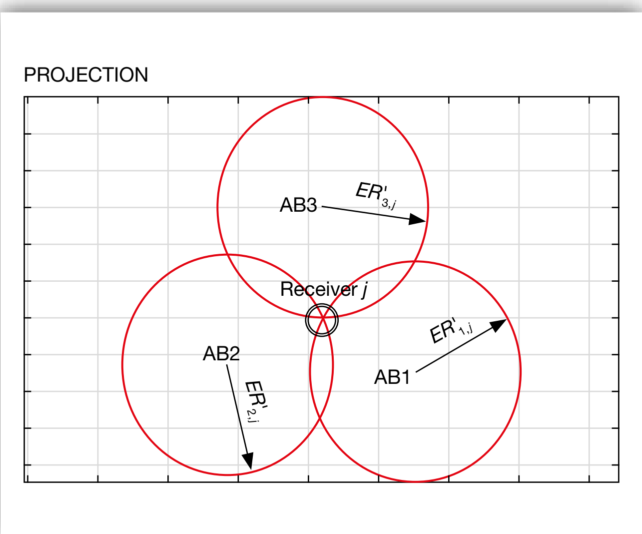


Figure 13. Triangulation method using *ER'*.

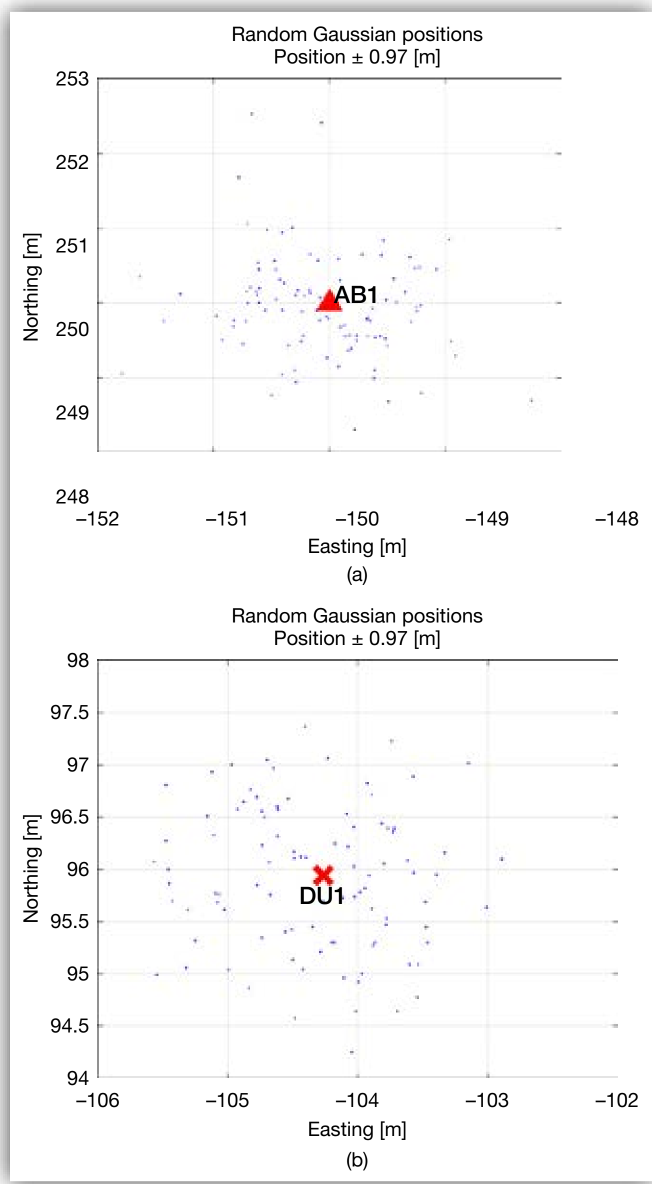


Figure 15. Locations studied in 100 measures (in blue) with random Gaussian distribution for positions. (a) Detail of AB1. (b) Detail of DU1.

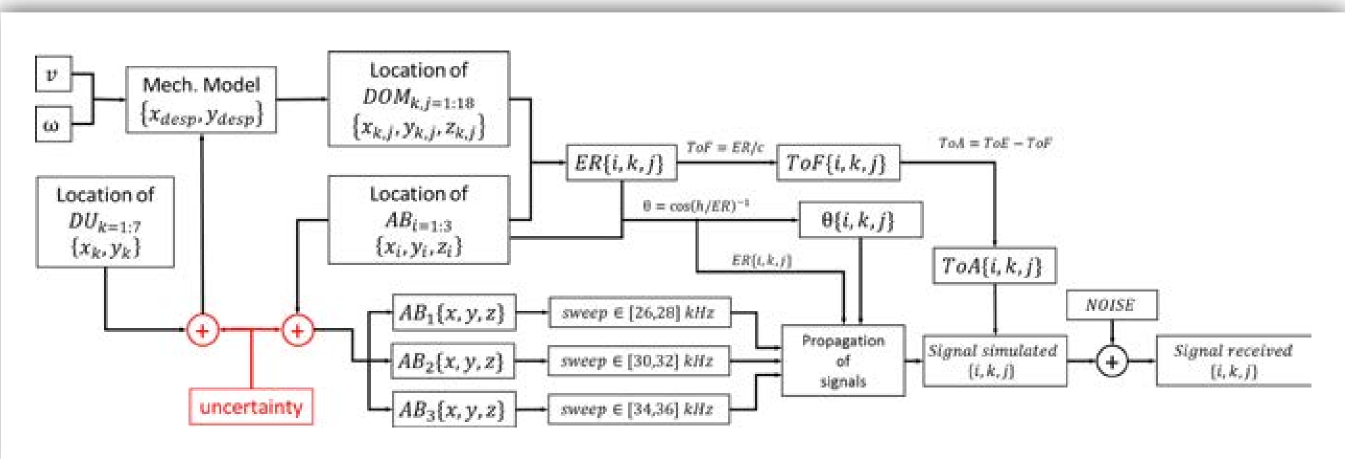


Figure 14. Simulation of the signal received applying uncertainty in locations of DUs and Abs.

All these differences are calculated for coordinates *x* and *y* in all iterations of the simulation to study the uncertainty of the triangulation method.

Once the simulation has all positions of DOMs from triangulation method (and reconstructed the *z* coordinate) in all iterations, the relative difference between the DU baseline and all DOMs for the *x* and *y* coordinates (*diff*1) is calculated. This will constitute the input for the line fit mechanical model, using the sea current velocity as a free parameter [4]

3. Results

The triangulation method for positioning has been studied for 3D systems (with *x*,*y* and *z* coordinates) and 2D system (using the projections, since z practically does not change). The 3D detection technique will not be shown here since results in larger uncertainties due to the fact that all the emitters are practically in a plane having also a noticeable uncertainty in the relative depth, and thus in the z. Therefore, it is better to constrain *z* from what you know from the structure of the DU and determine just horizontal coordinates x and y.

3.1. Acoustic simulation

The difference of distance between the "initial position" and the position detected by acoustic system, after triangulation, is shown in *Table 1*.

Table 1. Differences obtained by the acoustic positioning system.

x_{mean} [cm]	y_{mean} [cm]	x_{max} [cm]	y_{max} [cm]
1.9	20.0	5.2	42.9

The results of the acoustic simulation (*acous*) for the value of *diff*1 are shown in *Table 2*, compared with *diff*1 of the "initial position" from the Mechanical Model (*ini*).

Table 2. Results of diff1 in the acoustic system with 3 ABs.

*diff*1		*x* [cm]	*y* [cm]
ini	*DOM*1	5.8	5.8
	*DOM*18.	32.2	32.2
acous	*DOM*1	6.9±0.5	3.4±4.8
	*DOM*18.	39.4±4.9	19.1±42.3

3.2. Triangulation method

The triangulation method is tested with 100 iterations (pseudo-experiments). Their analysis allow to determine the values and uncertainties expected for the position of the elements and the three relative differences (*Table 3* and *Table 4*, and *Figure 16*). The values *diff*2 and *diff*3 are very similar (variations smaller than 5 mm), for this reason are presented in the same table.

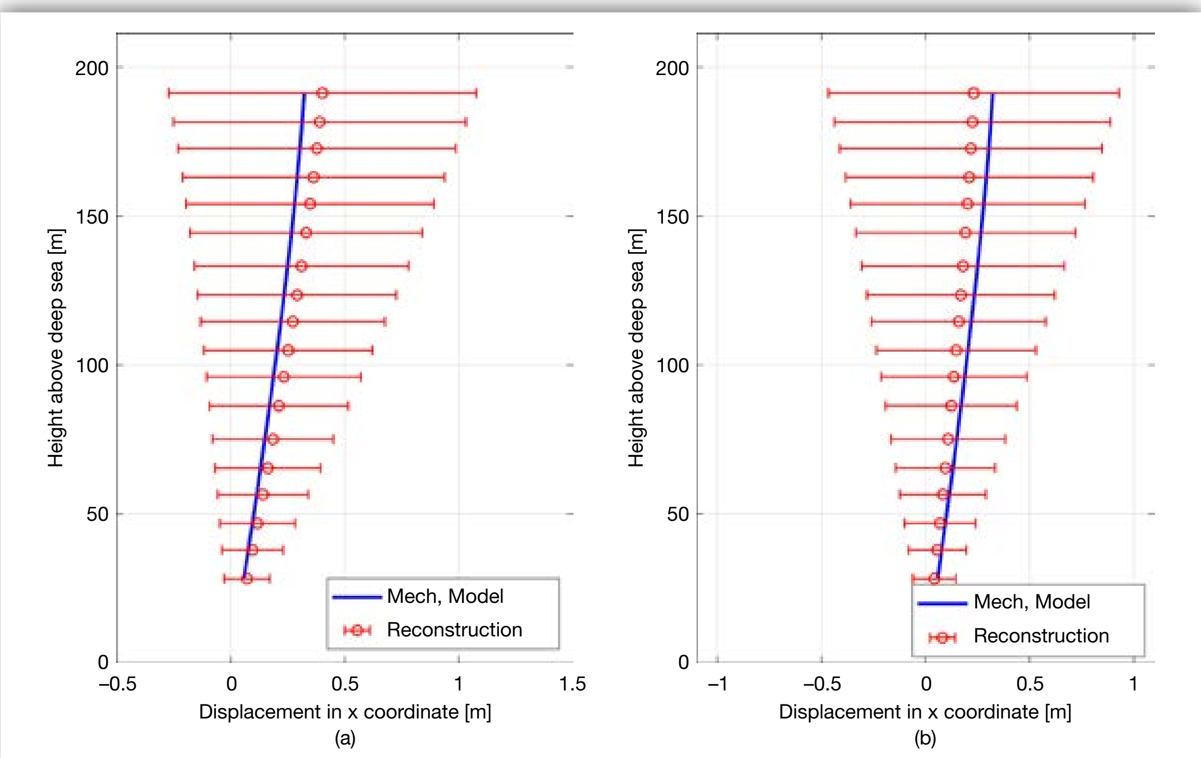


Figure 16. Reconstruction of the DU2 by Diff1 in triangulation method in coordinate (a) and coordinate (b).

Table 3. Results for *diff*1 in the acoustic system.

*diff*1		*x* [cm]	*y* [cm]
ini	*DOM*1	5.8	5.8
	*DOM*18.	32.2	32.2
acous	*DOM*1	7.2±9.8	4.2±9.4
	*DOM*18.	40.2±66.4	23.0±63.3

With these results, it is possible do the last step, a DU Line Fit Analysis using as input the acoustic positioning system data. From the positions of the 18 DOMs of the 7 DUs with respect to the respective base obtained by the triangulation method, *Diff1 acous* values, it is possible to do a fit using the mechanical model using the sea current velocity as free parameter. Studying in this way, the simulation allows to compare the reconstruction of the DU shape using only the acoustic detection system and applying to these positions the restrictions given by the mechanical model (see *Figure 17*).

The results obtained in the different steps can be determined by looking at *Diff1* from acoustic detection (*acous*) position and *Diff1* from the last reconstruction (*reconst*) compared with *Diff1* from initial position (*ini*). These comparisons are given as offsets, on the one hand, the *offset1* is the value from studying the difference between *Diff1 acous* and *Diff1 ini*, and on the other hand, the *offset2* is the value from studying the difference between *Diff1 acous* and *Diff1 reconst*.

As it can be seen in *Figure 18* the use of the DU line Fit reconstruction reduces the uncertainty in the determination of the position of the DOM.

4. Conclusion and next steps

We have performed simulations of the acoustic positioning system of KM3NeT, including the line shape model. From this work and [6] we can conclude that the performance of the acoustic system is good: the ToA can be determined accurately for the SNR expected. The distances can therefore be calculated with the required few cm accuracy.

In this paper, we have also addressed the case of ORCA Phase-1 with just three autonomous ABs, which are not synchronized. In spite of having an uncertainty of 1 m in the 3 coordinates of the ABs and DUs, the

Table 4. Results for *Diff*2 and *Diff*3.

*diff*2 ≈ *diff*3 [m]						
Coord. *x*						
DU1 to	DU2	DU3	DU4	DU5	DU6	DU7
M.M	-24.9	-12.6	-37.3	-46.5	-36.1	-57.5
acous	-25.3±0.8	-13.0±0.7	-37.3±0.8	-46.4±0.8	-35.4±0.7	-57.4±0.8
Coord. *y*						
DU1 to	DU2	DU3	DU4	DU5	DU6	DU7
M.M	-3.4	-23.0	16.7	-3.9	-22.4	-22.9
acous	-3.8±0.8	-23.0±0.8	16.2±0.7	-3.9±0.8	-22.3±0.8	-23.0±0.7

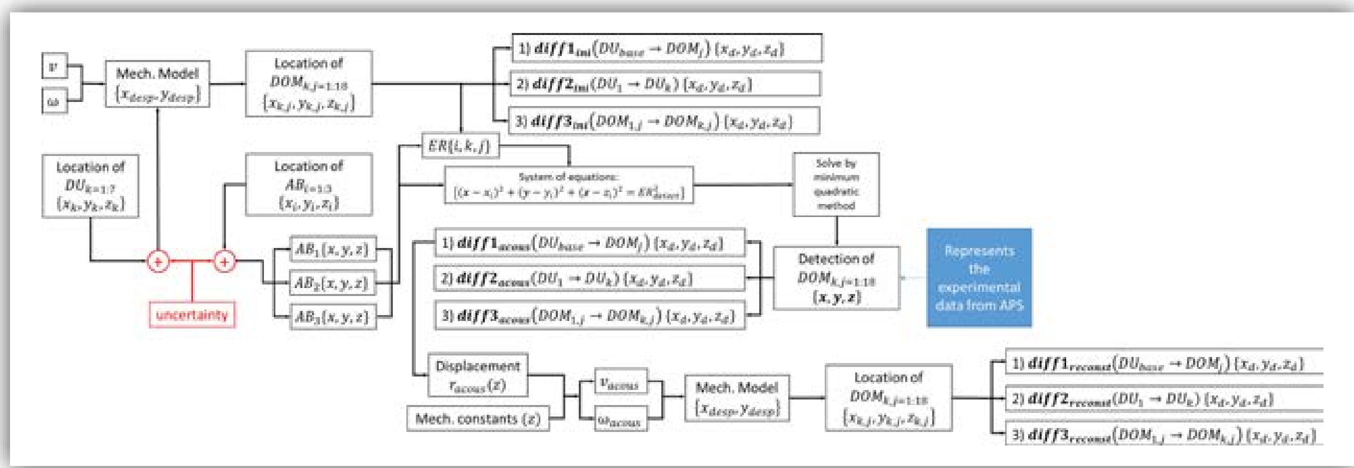


Figure 17. Diagram of all simulated system.

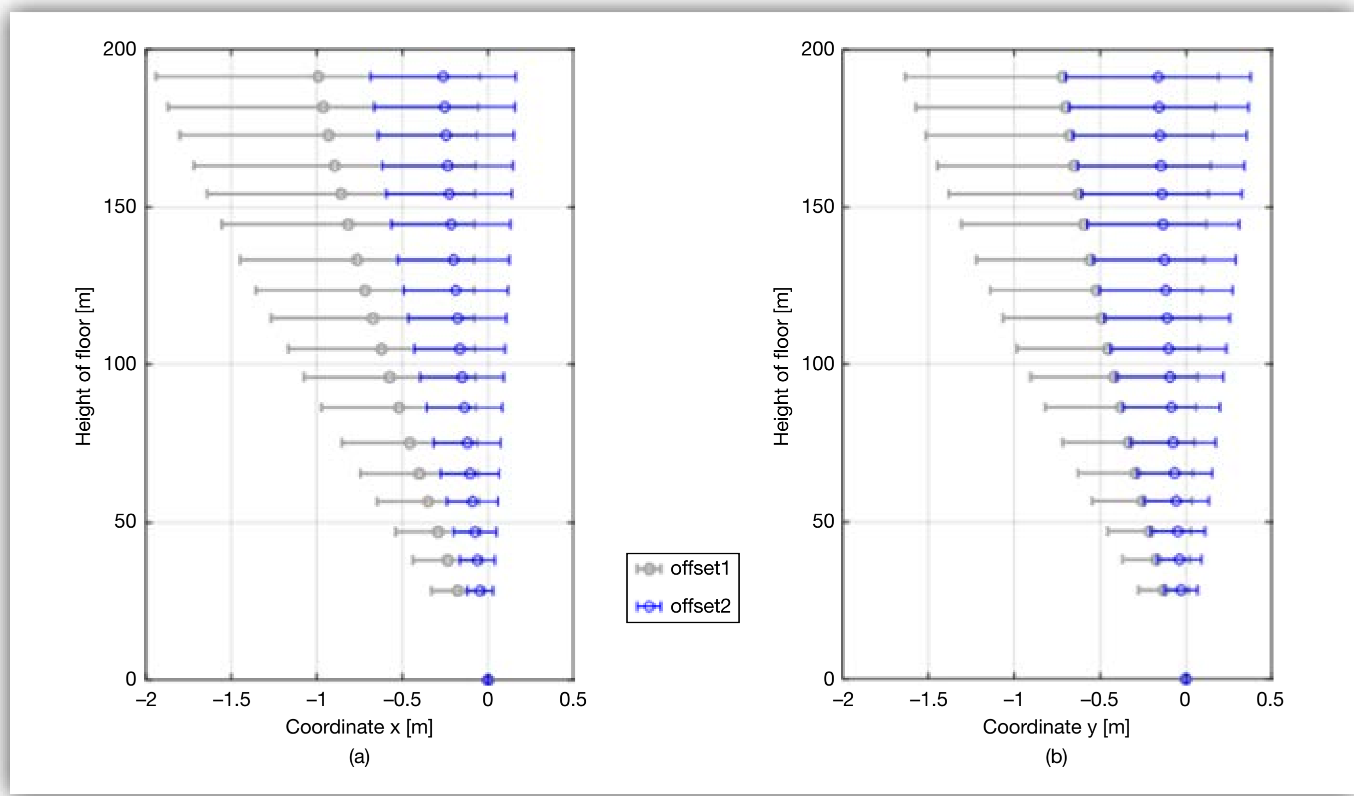


Figure 18. Offset1 (using only acoustics) and offset2 (acoustics + Mechanical Model Fit) values for each coordinate. (a) Coordinate x. (b) Coordinate y.

uncertainty obtained for the relative differences are smaller than half a meter. Although the results have been presented to a specific sea current velocity, results are very similar for common velocities, independently of its direction.

As next steps, we will deeper investigate in the systems so, to try to reduce the uncertainties, and once more synchronized ABs will be connected, it is expected that uncertainties will be reduced to ~ 10 cm.

5. References

[1] S. Adrián-Martínez, et al. (2016) "*Letter of intent for KM3NeT 2.0*", J. Phys. G: Nucl. Part. Phys, (43) 084001.DOI: 10.1088/0954-3899/43/8/084001

[2] S. Viola, et al. (2016) "Acoustic positioning system for KM3NeT", PoS (236) ICRC2015, 1169.DOI: 10.22323/1.236.1169

[3] M. ARDID (2009) "*Positioning system of the ANTARES neutrino telescope*", Nucl. Inst. Meth. (602), 174-176. DOI: 10.1016/j.nima.2008.12.033

[4] S. Adrián-Martínez, et al. (2012) "The positioning system of the ANTARES Neutrino Telescope", JINST (7) T08002. DOI: 10.1088/1748-0221/7/08/T08002

[5] L. E. Kinsler, et al. (2000) "*Fundamentals of Acoustics*". ISBN: 0-471-84789-5

[6] D. D.Tortosa, et al. (2018) "*Comparación de distintos métodos para la detección acústica en el detector de neutrinos KM3NeT*", XI Congreso Iberoamericano de Acústica –FIA18- p.388-395. Cádiz. ISBN: 978-84-87985-30-4

Construir a conciencia.

StoSilent
Setting
the tone in
acoustics.

Sistemas acústicos de Sto

www.sto.es | info.es@sto.com