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# The KM3NeT acoustic positioning system

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**on behalf of the KM3NeT Collaboration**

The KM3NeT Collaboration is building two underwater neutrino detectors: ARCA (Astronomy Research with Cosmic in the Abysses), deployed at 3500 m depth in the Ionian Sea, offshore from Sicily, aiming at the measurement of cosmic neutrino signals and at the detection of astrophysical neutrino sources; ORCA (Oscillation Research with Cosmic in the Abysses), deployed at 2500 m depth, offshore from Toulon, south of France, aiming at the measurement of the neutrino mass hierarchy. In both detectors, the direction and the energy of the interacting neutrinos are reconstructed through the water Cherenov technique. The Cherenkov light, induced by the charged particles resulting from the neutrino interaction, is measured by an array of optical sensors, installed on slender strings anchored on the sea bottom, called Detection Units (DUs). In order to effectively reconstruct particle tracks, the optical sensors coordinates must be known (in a known reference system) with an accuracy of a few tens of cm. Moreover, since the mechanical structures holding the optical sensors move under the effect of sea currents, their positions must be continuously monitored. In KM3NeT, the positioning is performed using an array of piezo-electric acoustic receivers and a long baseline of several acoustic emitters and hydrophones installed in fixed positions on the seabed. All the elements of the acoustic positioning system are synchronized with the detector master clock. After measuring the range between each emitter and receiver, position of receivers is obtained in real time via multilateration. First results obtained with the current minimal infrastructure (2 DUs and 3 emitters in the ARCA field) demonstrate that the acoustic system already achieves a resolution close to 50 cm. The full stream of acoustic data from each receiver is sent onshore and can be also utilized for environmental monitoring purposes and bioacoustic research.

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## 1. Introduction

The KM3NeT Collaboration is building two underwater neutrino detectors: ARCA (Astronomy Research with Cosmic in the Abysses), deployed at 3500 m depth in the Ionian Sea, offshore from Sicily, aiming at the measurement of cosmic neutrino signals and at the detection of astrophysical neutrino sources; and ORCA (Oscillation Research with Cosmic in the Abysses), deployed at 2500 m depth, offshore from Toulon, south of France, aiming at the measurement of the neutrino mass hierarchy [1] [2]. ARCA and ORCA use the water Cherenkov technique to reconstruct the energy and direction of neutrinos interacting inside or in the proximity of the detector. Both detectors are built with the same technology based on the use of multi-PMT (31 PMTs, 3" diameter) Digital Optical Modules (DOMs). 18 DOMs are arranged on a Detection Unit (DU), a slender string anchored on the sea bottom and tensioned by a buoy on the top. ARCA, comprising 230 DU, 700 m high, will have a total size of about 1 $km^3$. The size of ORCA will be a factor four less in all dimensions. Two different acoustic positioning systems (APS) are needed to provide mandatory information during the deployment and the operation phases of the KM3NeT telescope [4]. During the deployment phase, the so called absolute positioning system must provide the position of the telescope's mechanical structures, in a geo-referenced coordinate system, with an accuracy of about 3 meters. This is important for a safe deployment of the mechanical structures. Combining the absolute positioning system with a relative positioning system based on a built-in auto-calibrating Long BaseLine (LBL) of transponders, the APS must be able to determine the absolute position of the detector to allow safe deployment and, for scientific purposes, to determine the absolute pointing direction of the telescope (necessary for the localization of astrophysical sources). During the telescope operation phase, the data from the relative acoustic positioning system are used – in combination with compass and tilt, pressure, current and sound velocity data – to recover the positions of Digital Optical Modules (DOMs) in the deep sea with respect to the geo-referenced LBL. To achieve the target energy and angular resolution for the reconstruction of neutrino events, the position of each PMT must be measured with an accuracy of better than 30 cm, corresponding to the path traveled by a relativistic particle in water in about 1 ns.

## 2. Acoustic positioning methodology

In ARCA, the absolute position of the structures are determined through a commercial positioning systems based on Ultra Short BaseLine (USBL) technology, installed on the ship devoted to the deployment of the structures. Thanks to an acoustic transponder mounted aboard the remotely operated vehicle used for the underwater operations, it is possible to recover the positions of the structures from the ship, moving the vehicle in proximity of the objects to be positioned. In the ORCA site, the absolute positioning system is provided by a Long BaseLine (LBL) positioning system provided by the iXBlue [3] company. The system is based on the use of a Low Frequency (LF) rangemeter system named RAMSES, installed on the navigation boat, and of a LBL array composed by several fixed acoustic transponders, deployed on the seabed at known positions. The system uses acoustic signal in the 8-16 kHz frequency range, allowing for slant measurements with transponders up to distances of about 8000 m under optimal conditions. For acoustic travel time measurements, it can use monochromatic acoustic pulses or modulated frequency signals making it much more robust to acoustic environmental noise. The RAMSES system is coupled to an Inertial Navigation System (INS) to increase the global positioning accuracy and to improve robustness of the positioning system. Each object to be monitored must host at least one acoustic beacon.

The proposed relative acoustic system for both ARCA and ORCA relies on an "all data to shore" philosophy. This means that acoustic data acquired by the acoustic receivers are continuously digitized and sent to shore, where they are analyzed with a dedicated farm of PCs. This choice avoids the use of off-shore electronics for signal identification, reducing power consumption and costs and improving the system reliability and versatility. The KM3NeT relative APS is composed by three main sub-systems: 1) an array of acoustic receivers rigidly connected to the telescope mechanical structures; 2) a so called Long BaseLine (LBL) of acoustic transmitters (beacons) and receivers, anchored on the seabed at known positions; 3) a farm of PCs for the on-shore acoustic data analysis. The positions of the acoustic receivers are calculated on-shore by measuring the ToF (Time of Flight) of the LBL beacons' signals on the acoustic receivers, thus determining, via multilateration, the position of the acoustic receivers with respect to the geo-referenced LBL. The signals emission of acoustic transmitters (beacons) is set in the range of frequencies 20÷40 kHz. In this range acoustic signals can effectively propagate in water: at 2 km distance the recieved amplitude for a 32 kHz tone emitted with a pressure level of 180 dB re 1 $\mu$Pa at 1 m, is about 110 dB re 1 $\mu$Pa and it can be easily recognized by the acoustic receivers of the telescope. Since the whole array of receivers is synchronized with the detector master clock ( and thus with the GPS time delivered from shore), the proposed APS can perform precise ToF measurement. ToF measurements between different LBL beacons and receivers are used to perform LBL auto-calibration in the deep sea: this means that they are used to determine and monitor their relative distance. The expected accuracy in determination of their relative position is of the order of few cm. Two kinds of technologies for acoustic sensors are installed aboard the Detection Units (DUs). An "external" digital hydrophone, installed in each DU base and also used as receiver in the autocalibrating LBL, and an "internal" digital piezoelectric sensor, installed inside the DOM [5] [6]. A major step of KM3NeT, with respect to previous technology [7] is the use of digital acoustic receivers (DAR), that sample the analogue piezoelectric signal, and provide a PCM-like protocol (pulse code modulation, such as AES-EBU) to the Central Logic Board (CLB) installed in each DOM and DU Base. The use of AES protocol simplifies interface with CLB and permits to use standard audio libraries. The acoustic positioning hardware and software architecture is fully integrated in the KM3NeT DAQ system. Time of Arrival (ToA) of emitter signals to each DOM is extracted on shore by an on-line module, called Acoustic Data Filter (ADF). ADF searches for a maximum of the correlation function between the acoustic data stream and the expected signal on time windows 670 ms long with an overlap between consecutive windows of 40 ms. The amplitude of the maximum value of the correlation function in each windows is used as a quality factor (QF) to discriminate beacon signals from background noise. If QF is above an established threshold, ToA information is stored on the detector database. Each ToA entry on database includes the identification code of the receiver, the identification code of the emitter, the extracted ToA written in UTC (Coordinated Universal Times) with a resolution of 1 $\mu$s and the related QF value. Finally, an additional software reads, from the database, the ToA packets acquired during a beacon emission cycle by all DARs, the time of emission (ToE) of the emitters and the position of the beacons (after LBL calibration) and eventually calculates the average DARs' position during a positioning cycle (a few minutes) using a multilateration algorithm. The Sound Velocity Profile (SVP) along the water column where the DU is installed must be measured. A schematic view of the DOM positioning software is shown in Figure 1. The multilateration code runs using, as initial value, the DOM positions calculated in the previous cycle. For the very first cycle the nominal positions of the DOMs are used.

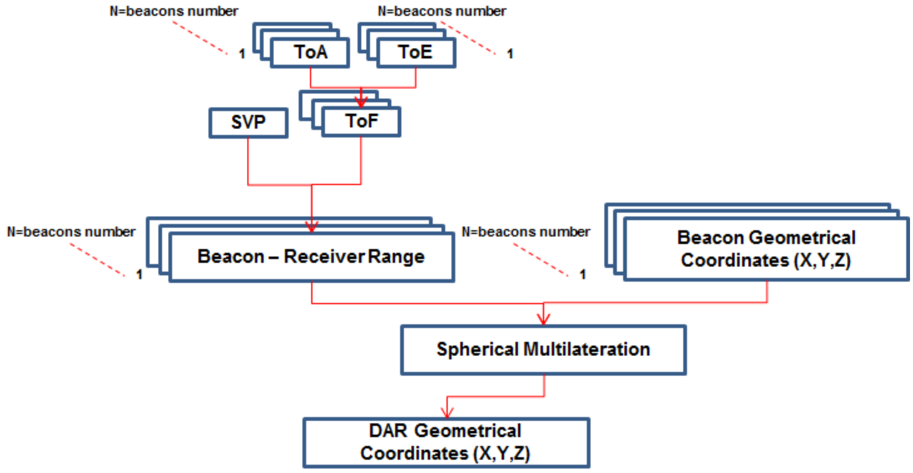


**Figure 1:** Schematic view of the DOM positioning software. The distance between each beacon and each DAR is calculated from the delay – Time of Flight (ToF) – between the Time of Emission (ToE) of the acoustic pulse and the corresponding Time of Arrival (ToA) to the DAR, considering the Sound Velocity Profile (SVP) along the sound path. If the positions of the LBL beacons are known, DAR positions can be recovered from beacons-receivers ranges through spherical multilateration.

## 3. First results in situ

The current underwater infrastructure in the ARCA field includes 2 DUs (ARCA-DU1 and ARCA-DU2) and 3 emitters. Two of the three emitters are part of the auto-calibrating LBL and are installed on the two first Junction Boxes of the ARCA seafloor network that were put in operation. Waveform, amplitude, frequency, duration and repetition rate of these emitters can be set through a serial communication based on RS232 standard. The third emitter installed in ARCA field is an autonomous acoustic beacon, fed by a battery pack installed in a pressure resistance glass sphere. This emitter transmits a pattern of 6 pseudo-random pulses (spaced by $\sim$ 2 sec) with a period of about 12 seconds. Each pulse is a sinusoidal packet of 32 kHz and its duration is about 5 ms. First measurements in situ have demonstrated the functionality of the acoustic data acquisition chain and the capacity of the system to disentangle pulses produced by different emitters. A study on ToAs related to the acoustic pulses emitted by the autonomous beacon, located at about 200 m and 250 m from the two DU bases, allowed for the evaluation of the accuracy of the system on ToA measurements. Currently, the accuracy for each single ToA measurement is about 300 $\mu$s, corresponding to an uncertainty on range measurement of about 50 cm. The precision can be improved with statistics. The median values, calculated every 5 minutes, of ToAs to the lowest DOM of ARCA-DU1 modulo the period of the beacon pattern, over a period of 48 hours (from 2017/03/16-18:00:00 UTC to 2017/03/18-18:00:00 UTC), are reported in Figure 2. The plot refers to only one of the 6 pulses of the beacon pattern. The width of the curve indicates that the uncertainty on ToA is reduced to less than 50 $\mu$s, corresponding to about 8 cm in the range determination. The slow variations, up to a few hundreds $\mu$s, can be attributed to the movements of the structure under the action of underwater currents.

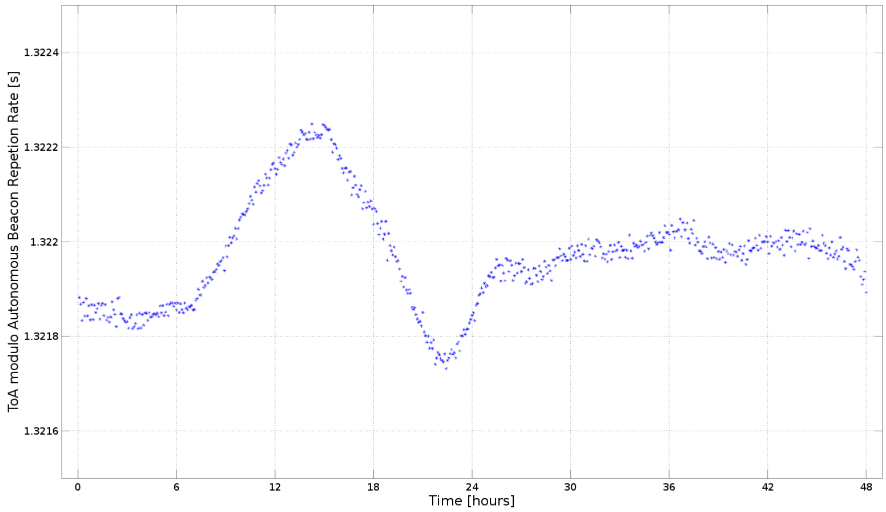


**Figure 2:** Median values, calculated every 5 minutes, of the ToAs to DU1 - DOM1 modulo the autonomous beacon repetition rate. The figure referes to one of the six pseudo-random pulses of beacon pattern.

To evaluate the consistency of the ToA measurements, the difference between ToAs on each DOM in operation and the related ToAs on the lowest DOM of ARCA-DU1, used as a reference, has been measured. Measurements have been compared with the expectation, assuming DUs perfectely vertical. In the comparison, nominal positions of beacon and DUs bases on the seabed have been considered taking into account the positioning accuracy provided by the USBL system during the deployment of the structures. In Figure 3 and Figure 4 the median values of the difference between ToAs to each operating DOM and ToAs to the lowest DOM of ARCA-DU1 are shown (blue dots). The band enclosed by the two red lines referes to the expected time difference, considering the uncertainty on the absolute positions of the autonomous acoustic beacon and of the DU bases on the sea floor. Time of flight of the autonomous beacon signal to reach each DOM has been calculated by using the sound velocity profile, measured at ARCA site in a previous sea campaign. For the comparison, data acquired during a six hour period, from 2017/03/16-18:00:00 UTC to 2017/03/17-00:00:00 UTC, were used. The comparison shows that measurements are in agreement with the expectations.

## 4. DOM orientation monitoring

For both KM3NeT ARCA and ORCA, to reconstruct the Cherenkov cone of charged particles resulting from neutrino interactions – and hence the direction of the incident neutrino – with high precision it is also required to know the orientation of the DOM. The DOM orientation, and consequently the field of view of the 31 PMTs, is provided independently by a custom Compass and Tilt Board, soldered on the Central Logic Board (CLB), placed in a fixed position inside the DOM.



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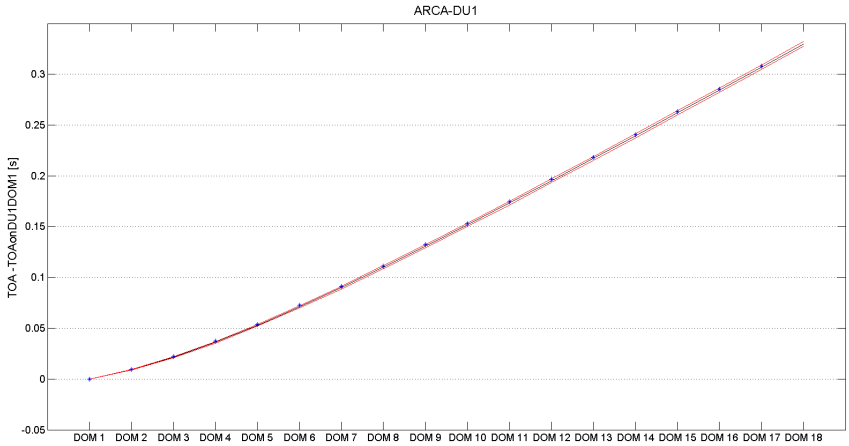


**Figure 3:** Median values in six hours of the difference between ToAs to each DOM in operation in DU1 and ToAs to the lowest DOM of DU1 are shown (blue dots). The band enclosed by the two red lines refers to the expected time difference, assuming the DU perfectely vertical and considering the position accuracy of the autonomous acoustic beacon and of the DU base.

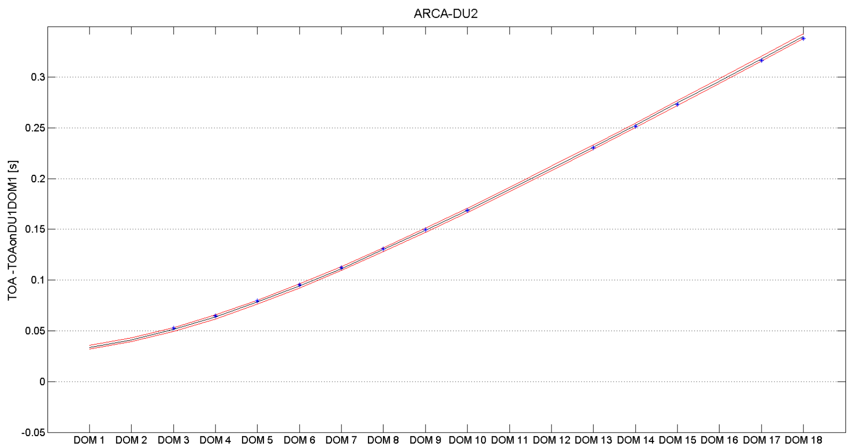


**Figure 4:** Median values in six hours of the difference between ToAs to each DOM in operation in DU2 and ToAs to the lowest DOM of DU1 are shown (blue dots). The band enclosed by the two red lines refers to the expected time difference, assuming the DU perfectely vertical and considering the position accuracy of the autonomous acoustic beacon and of the DU base.

The board is equipped with a 3-axis magnetometer and a 3-axis accelerometer. Sensors data are continuously sent to shore allowing the measurement and the monitoring of the yaw, pitch and roll angles of each DOM. Pre-calibration of the boards must be carried out before their integration into the DOM to compensate internal magnetic field effects. Thanks to the Compass and Tilt Board, DOM orientation is recovered with a precision of better than $3^\circ$. Simulations have demonstrated that no detectable effects are expected in the angular reconstruction accuracy of track-like events for uncertainty on orientation up to $9^\circ$ (three times the measured uncertainty) [2]. In Figure 5, values of yaw, pitch and roll of the DOM7 of ARCA-DU1 over a time period of 7 days are reported. A periodicity of about 20 hours is observed. This periodicity can be attributed to inertial motions induced by the Coriolis' force.

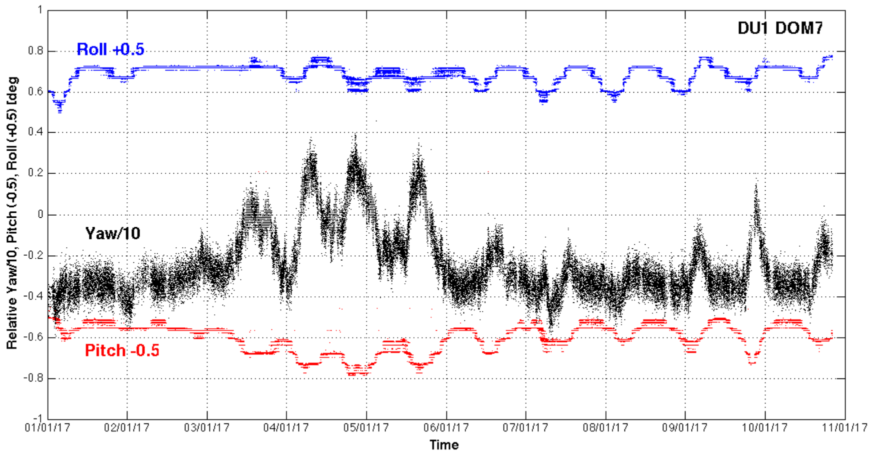


**Figure 5:** Yaw, pitch and roll angles of DOM7 of ARCA-DU1, measured over 7 days of data acquisition. To report yaw, pitch and roll in the same scale, yaw values have been scaled by a factor 1/10 (black) and an offset of - 0.5° e + 0.5° have been added to pitch (red) and roll (blue) angles respectively.

## 5. Conclusions

The installation of a hybrid positioning system based on an acoustic positioning system and on a Compass and Tilt Board is ongoing at the two KM3NeT detector sites. First measurements in KM3NeT ARCA with an incomplete acoustic positioning system, have demonstrated that it is possible to measure ToAs of the acoustic calibration pulses to DAR with an accuracy of better than 50 $\mu$s, corresponding to an uncertainty on range measurements of about 8 cm. This accuracy on ToA measurements will guarantee, after the complete installation of the auto-calibrating Long Base-Line, an uncertainty for DOM positions of a few tens of cm. In a following stage, the information provided by the acoustic positioning system and by Compass and Tilt Boards will be combined with information from sea current intensity and direction and with mechanical information in a DU line shape algorithm, capable to predict the behavior of the line and to interpolate the DOM positions and orientations in case of malfunctioning of a DAR or of a Compass and Tilt board. It is also worth mentioning that the use of the described system allows sharing of acoustic data with the Earth and Sea Science Community for several research subjects such as: marine monitoring, biology, geophysics and oceanography.

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