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ACOUSTIC BEACON FOR THE POSITIONING SYSTEM OF THE UNDERWATER NEUTRINO TELESCOPE KM3NeT

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ABSTRACT

The design and development of an acoustic beacon as part of the positioning system for the underwater neutrino telescope KM3NeT is presented. Acoustic positioning system is used to monitor the position of the optical sensors of the telescope (with 10 cm accuracy over distances of about 1 km), in which the acoustic beacons are the active elements. The acoustic beacon is able to generate high-power short signals in a frequency range of 20-60 kHz, hence signal processing techniques can also be used to improve the performance of the positioning system.

1. INTRODUCTION

The Acoustic beacons have been developed to be part of the acoustic positioning system (APS) for the multi-cubic-kilometre underwater neutrino telescope KM3NeT located at the depths of the Mediterranean Sea. Currently, KM3NeT project is in its first construction phase, after the preparatory and design phases. At the end of this phase the detector will consists of 24 Detection Units (DUs) deployed off-shore in Capo Passero, Italy, (KM3NeT-IT) and 7 DUs, deployed off-shore in Toulon, France (KM3NeT-FR). Each DU hosts 18 digital optical modules (DOMs), each one equipped with 31 photo-multipliers tubes (PMTs) [1].
The KM3NeT telescope will detect neutrinos by measuring the Cherenkov light emitted by charged secondary particles produced in neutrino interactions with the sea water or the rock beneath. Since neutrinos interact so weakly, a huge volume of water must be observed to collect a sufficient number of such events. The direction of the incoming neutrino can be reconstructed with the telescope and its energy estimated. Accumulations of neutrino events pointing to particular celestial directions will establish the coordinates and characteristics of cosmic accelerators or other astrophysical neutrino sources.
During the telescope operation, in order to effectively reconstruct muon tracks, generated by the interaction of cosmic neutrinos with water nuclei, via the optical Cherenkov technique, the coordinates of the optical sensors must be known with an accuracy of about 10 cm. In the deep sea, DUs are anchored to the sea bed but they are free to move along their vertical expansion under the effect of currents, thus their positions must be determined and monitored. A long baseline (LBL) of acoustic transmitters placed on the seabed in known positions and an array of

acoustic receivers rigidly connected to the mechanical structures of the telescope will be used, therefore the optical sensor positions could be continuously calculated via triggered emission of acoustic signals. The distances from acoustic emitters and receivers of the line are of the order of 1 km, so acoustic signals emitted suffer a considerable attenuation.

2. LONG BASE-LINE (LBL) POSITIONING SYSTEM

The LBL positioning system of KM3Net is composed by an array of acoustic transmitters and receivers hosted on the DUs bases and on the Calibration Units bases (CBs). Each DU base will host a digital hydrophone, each CB will host an acoustic beacon and a digital hydrophone placed at known distance from the beacon. The LBL of the acoustic beacons installed on the CBs is complemented by an array of autonomous acoustic emitters (battery powered and driven by local clock) placed outside the footprint of the telescope, that improve the resolution of triangulation calculation for receivers placed on DU at the edge of the telescope field. Moreover, autonomous beacons must be used, during the installation of the first CBs, to create a temporary LBL field [2].

The positions of acoustic beacons, receivers and autonomous beacons must be geo-referenced during the deployment operation using GPS signal, available on board the ship that performs the deployment, with an accuracy of ±1 m. The main LBL system is time-synchronized and phased with the detector master clock. This allows the implementation of LBL auto-calibration and the possibility to accurately measure the Time of Flight (ToF) of acoustic signals emitted by each acoustic beacon to reach the acoustic receivers on DUs. The LBL acoustic beacons are reconfigurable by dedicated RS-232 bidirectional link between shore station and CU base electronics: acoustic emission signal parameters (amplitude, waveform, and timing) can be set for “in situ” optimization of the signal detection.

3. LBL ACOUSTIC BEACON

The acoustic beacon (MAB-100) developed by our group in cooperation with Mediterráneo Señales Marítimas SLL for the LBL positioning system is a broadband range acoustic emitter (20 kHz - 60 kHz) able to work at rating depths up to 400 bar in underwater environments. It provides the emission of short intense signals (Sound Pressure Levels of 180 dB re 1 µPa @ 1 m at 34 kHz) and has LBL functionality. The system is composed by a piezo-ceramic transducer and an electronic board integrated in an only piece system by a cylindrical hard-anodized aluminium vessel (Fig. 1) The transducer is a Free Flooded Ring (FFR SX30). The electronic board is specifically design to fulfil the positioning system requirements of the telescope, enabling the transducer communication and the signal emission control and amplification. It disposes of a serial interface communication via RS-232 for signal configuration from shore.

Figure 1. Acoubeacon MAB-100 device

3.1. AcouBeacon Piezo-Ceramic Transducer

The FFR SX30 acoustic transducers are able to work in the frequency range of 20 kHz to 50 kHz with transmitting voltage responses of 130 dB re 1 µPa/Volt @ 1 m at 30 kHz. The maximum input power is 300 W with 2% duty cycle. They are able to operate at very large depth, satisfactory tested up to 440 bar maintaining good stability. These transducers have an omnidirectional directivity pattern on the radial plane and a toroidal (60°) directivity pattern on the axial plane [3, 4].

In order to ensure the transducer holding and protection, the nude transducer is moulded with a polyurethane material joined to a BH2M hard-anodized aluminium connector as shown in Fig. 2. It is screwed into one side of the vessel and connected to the electronic board placed inside.

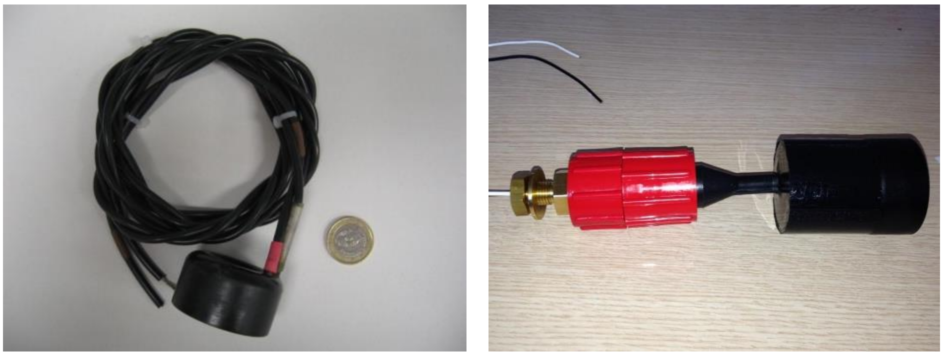

Figure 2. Nude (left) and molded (right) FFR SX30 Transducer

3.2. Acoustic specifications of the AcouBeacon

The *AcouBeacon* emits a Sound Pressure Level (SPL) of 180 dB re 1 µPa @ 1 m at 34 kHz with a variation of ± 6 dB in the frequency range of 20 kHz to 60 kHz. The radial beam pattern is omnidirectional with ± 2 dB for each work frequency and the axial beam pattern is toroidal with ± 10 dB of variation at 60º and ± 5 dB at 180º. The acoustic emission parameters are configured by commands through a RS-232 serial interface allowing signal reconfiguration from shore. There is a graphical interface for facilitating the user interaction. The signals parameters can be configured as following:

- Signal Emitted length: from 0 to 50 ms.
- Maximum emission amplitude: 180 dB @ 34 kHz re 1 µPa a 1 m.
- Type of acoustic signals:
    - Monochromatic signals configurable from 1 kHz to 80 kHz.
    - Sine Sweep signals configurable from 1 kHz to 80 kHz.
    - Maximum Length Sequence (MLS) signals with lengths from 5.12 ms to 40.96 ms (from 10th to 13th order and sampled at 200 kS/s).
- Modality of emission: external trigger response (LVDS with galvanic isolation). It disposes two operation emission modes; single and automatic (continue) emission.
- Variable temporal interval of emission between a signal and the successive one for the automatic emission mode from 0.5 s to 300 s.

The sound pressure level (dB re 1µPa@1m) of the acoustic beacon obtained with different capacitor charge (5V, 20V, 40V and 60V) is shown in Figure 3, in both radial and axial directions. Figure 4 shows the *AcouBeacon* directivity at axial direction.

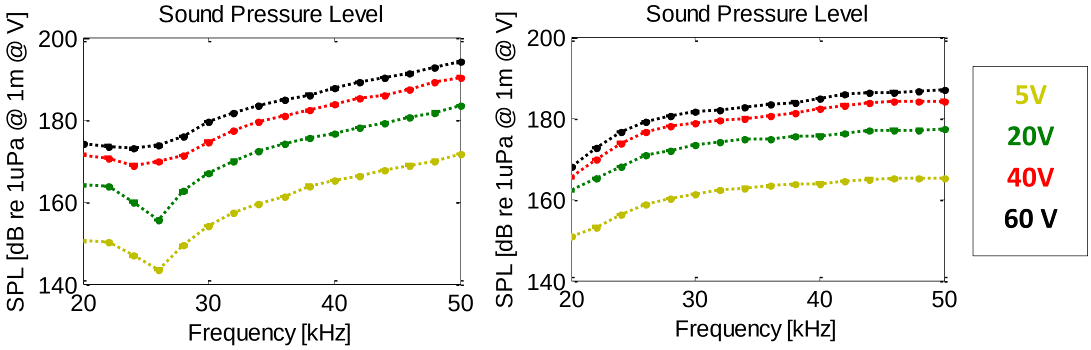

Figure 3. Sound Pressure Level (SPL) of the Acoubeacon at axial direction (left) and radial direction (right) for different capacitor charge.

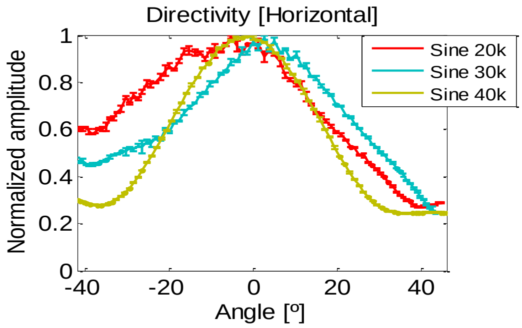

Figure 4. Directivity of the Acoubeacon

Positioning acoustic pulses will be emitted in the range of frequencies from 20 kHz to 50 kHz. In this range acoustic signals emitted in water with a SPL of 180 dB re 1 μPa at 1 m can effectively propagate until a distance of 2 km with about 110 dB re 1 μPa (depending on frequency) and it can be easily recognised by the acoustic receivers of the telescope.

3.3. Electronic specifications of the Acoubeacon

The *Beacon Board* has been carefully designed to accomplish all the positioning requirements, as well as, to optimize and amplify the signal power emission [5]. The board is piloted by a dedicated electronics integrated at the base of the Calibration Units (CBs) that provides the bidirectional link to shore; this enables emission signal reconfiguration for 'in situ' signal detection optimization. Acoustic waveforms to be emitted are stored in a local memory that can be updated from shore via RS-232 link. The signal emission trigger is received from the CB electronics, synchronized with the detector master clock. The time synchronization and calibration with respect to the detector master clock is accurate and stable. The technical specifications of the Acoubeacon electronics are described in Table 1.

Supply Voltage	12 V
current consumption	250 mA
Communications	Serial Port RS-232. Baud rate 9600, 8bits No parity 1 stop bit
Trigger Signal	Differential 1Vpp galvanic isolated Accuracy >±1μs
Emission Latency	<10 μs
Synchronization accuracy	<1 μs
Dimensions	Three boards (240x70mm all)
Lifespan	>=20 years

Table 1. Electronic specifications of the Acoubeacon for the LBL.

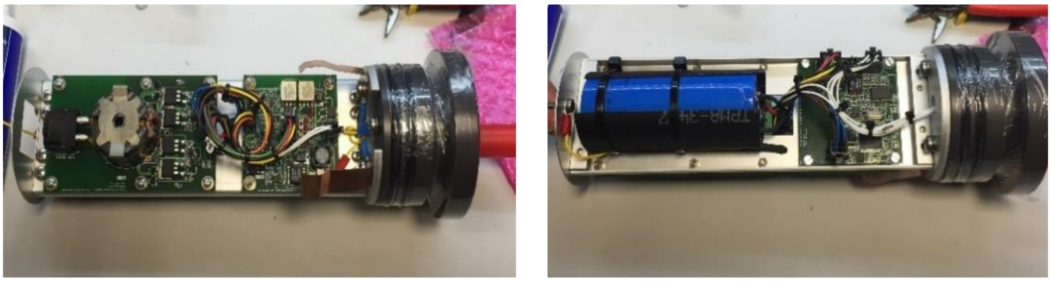

Figure 5. Acoubeacon Board

The electronic beacon board consists of three boards (Fig. 5): In the block diagram the yellow part is related with the DsPIC Board, the orange part related to the Supply Board and the red one to the Bridge Board.

The DsPIC Board has the main DsPIC processor that generates the PWM signal for the class D amplifier, a RS-232 isolated driver to receive the configuration commands protecting the supply of the telescope from emission noise, a galvanic isolated differential trigger reception to synchronize the emission of the beacon, a flash memory to store configuration and signals, and a temperature and humidity sensor to check the internal vessel status. The DsPIC board can also be connected to an external RS485/MODBUS pressure and temperature sensor that can check the external vessel conditions.

The Supply Board receives the 12 V external supply and uses it by means of a common mode filter and a current limiter that protects the telescope supply from noise and inrush current. After this protection the board has two DC-DC converters; one to feed the DsPIC board with 5 V and the other to provide 60 V for the emission. The 60 V are used to charge/discharge the main capacitor in the Bridge Board using a constant current source and a constant current sink. The main capacitor is charged slowly up to the desired emission voltage which is read from the main DsPIC using an ADC input.

Finally, the Bridge board consists of a power Mosfet H Bridge which amplifies the PWM signal that comes from the DsPIC using the energy stored in the main capacitor. The H Bridge is coupled to the transducer through a transformer that reduces the impedance.

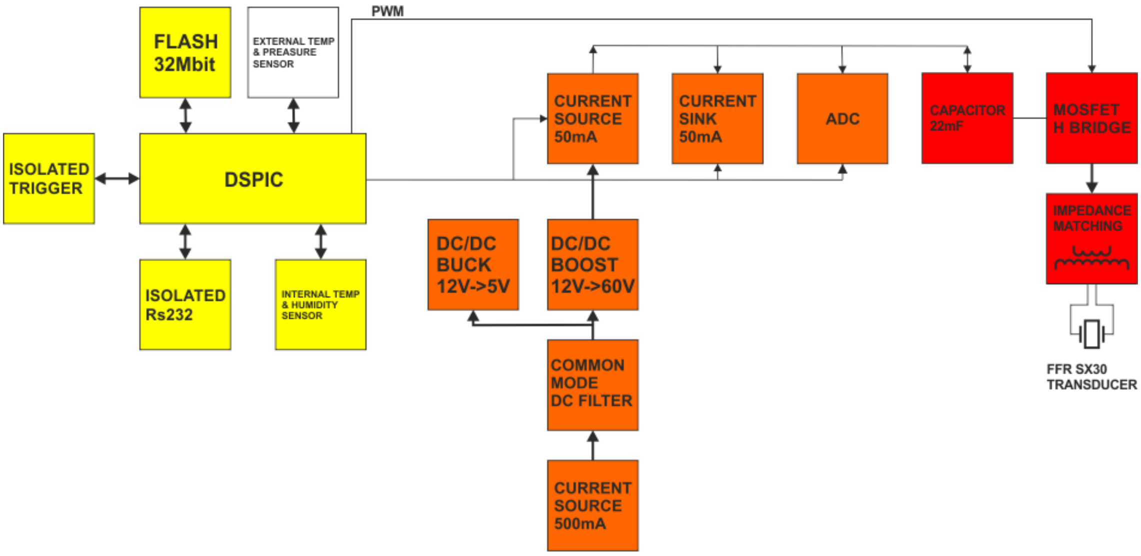

Figure 6. Block diagram of the electronic board

3.4. Mechanical specifications of the AcouBeacon

The AcouBeacon mechanical assembly consists of a cylindrical pressure vessel with a transducer screwed on the front endcap and hold firmly with a clamp (Fig. 7). The total length of the system is 575 mm; 400 mm length of the vessel including connector and 175 mm length of the complete transducer. The pressure vessel is a sealed system that contains the internal electronics in a secure environment, it isolates the electronics from external pressure and water and keeps them in proper humidity conditions. It is able to safely support pressure levels up to 400 bars.

The pressure vessel is composed of a closed aluminium hull and two removable endcaps with collar hulls and a light inner chassis where the electronic board is located. The endcaps have double O-ring seals to ensure sealing and closing by collar hulls. There are entries on both end caps of the vessel; one in the rear endcap for the passage of the power supply to the electronic board, using a Seacon Microwet MC-BH-6M hard-anodized aluminium connector, and one on the front endcap for the acoustic transducer connection to the board through a BH2M hard-anodized aluminium connector. The vessel material is hard anodized aluminium L6082-T6 of 60 microns and the hardware used is AISI316 (A4).

The acoustic transducer FFR SX30 is located in the front of the vessel conveniently moulded to cable signal using a polyurethane mould. The moulded transducer joint is subject to the vessel by means of a plastic (Arnite) clamp that guarantee the correct stability and strength of the issuer, without affecting the acoustic properties of the transducer, especially the directivity.

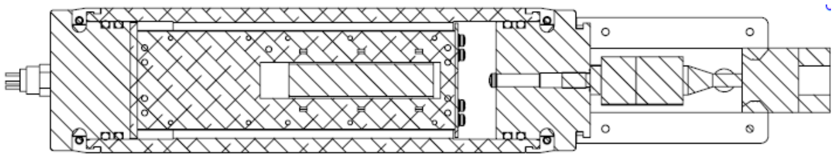

Figure 7. Drawing of the Acoubeacon, internal mechanical structure.

4. SIGNAL PROCESSING TECHNICS FOR DETECTION OPTIMIZATION

Protocols and post-processing techniques have been developed for the correct detection of the signals used for the positioning system. The distance from the emitters and receivers can be of the order of 1-2 km, therefore acoustic emitted signals suffer a considerable attenuation and arrive to the acoustic receivers of the detection units with a low signal to the environmental noise ratio. The noise masks the signal making its detection and the accurate knowledge of its arrival time a difficult goal [6].

The time of arrival (ToA) is determined by the difference between the emission time and the initial time of the receiving signal. The receiving time is obtained by two different methods: the threshold method used for sine signals mainly and the cross-correlation method of the received signal used mainly for the broadband signals: sine sweep and maximum length sequence (MLS) signals [7].

The threshold method determines the initial time of the received signal by taking a rise time value of the received signal envelope after applying a band-pass filter centred in the frequency of the emitted signal. The cross-correlation method determines the arrival time of the received signal by taking the interval of time corresponding to the maximum peak of the cross-correlated signal with the expected emitted signal. This technique is more favourable for broadband signals (sweeps and MLS) because they have a narrower correlation peak and consequently the mean peak is easier to discern than the other peaks. Figure 8 shows a tone, a sweep and MLS received signals with a distance of 112.5 m between emission and reception (E-R) in some measurement tests made in Gandia's harbour. On the top, the receiving signals in time domain after applying a high order band pass filter are shown (the original recorded signal in time is noisy so the receiving signal is masked). On the bottom, it can be seen the cross-correlation of each signal (without prefiltering) where direct signal reflections are easier and more effective to discern that working in the time or frequency domain, especially for the broad bandwidth signals (narrower auto-correlation peak).

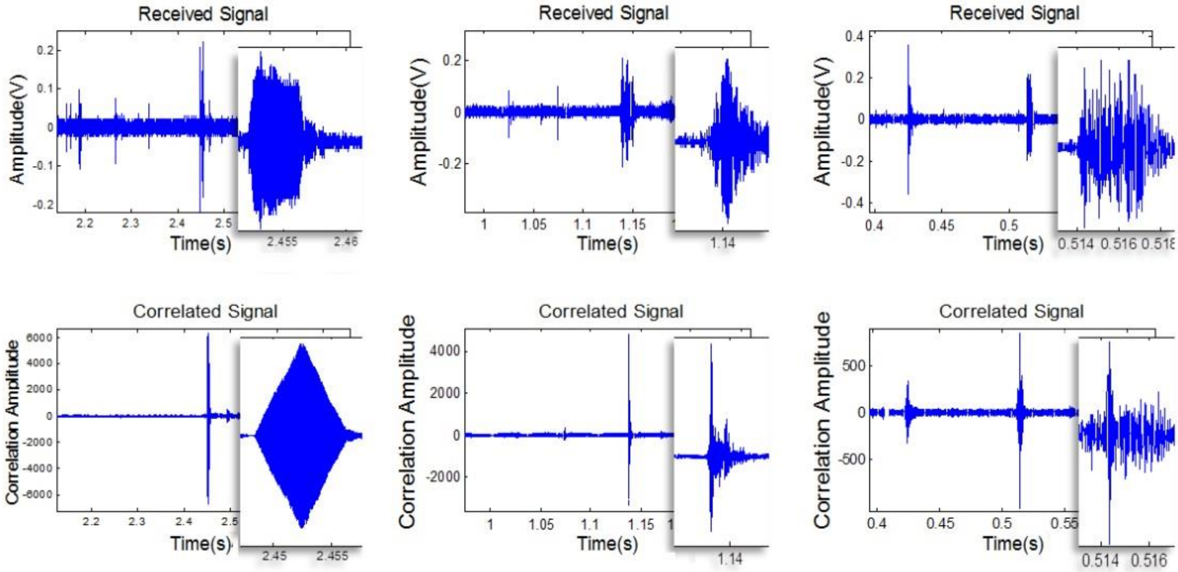

Figure 8. Example of recorded signals at 112.5 m E-R in the harbour of Gandia.

In situ test with the first's acoustic beacon prototypes have been performed in the neutrino telescope infrastructures installed in Capo Passero (NEMO) [8] and in ANTARES site [9, 10]. The emitted signals were sine signals of 20 kHz, 30 kHz and 40 kHz, sine sweep signals from 20 kHz to 48 kHz and from 28 kHz to 44 kHz, and MLS signal.

The data recorded in NEMO tower test (3500 m depth) was taken by hydrophones from all floors of the tower in which the emitter is located on the base. The distance from emitter to the first floor is about 100 m and between floors is around 40 m and the line has a total of 8 floors with two hydrophones per floor. As an example of the ToA obtained at the NEMO test, Fig. 9 shows the ToA obtained from the sine sweep signal from 20 kHz to 48 kHz applying the cross-correlation method. Table 2 shows the stability of the ToA values obtained from all hydrophones per signal.

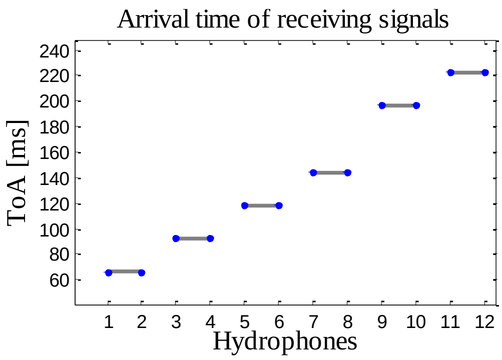

Figure 9. Time of arrival (ms) with the 20 kHz- 48 kHz sine sweep.

	THRESHOLD METHOD	CORRELATION METHOD
SIGNAL	SIGMA [ms]	SIGMA [ms]
Sine 20 kHz	0.065	0.103
Sine 30 kHz	0.031	0.046
Sine 40 kHz	0.029	0.029
Sweep 20kHz48kHz		0.027

Table 2. Stability of ToA values from all hydrophones per signal.

The results of the tests performed in situ show that the time of arrival obtained matches with the expected distances from the emitter to the hydrophones, as well as, a good stability is obtained.

The signal to noise ratios obtained by using the filter and threshold in time and cross-correlation methods to determine the amplitude; are shown in Fig. 10 for a distance between the emitter and receiver of 180 m.

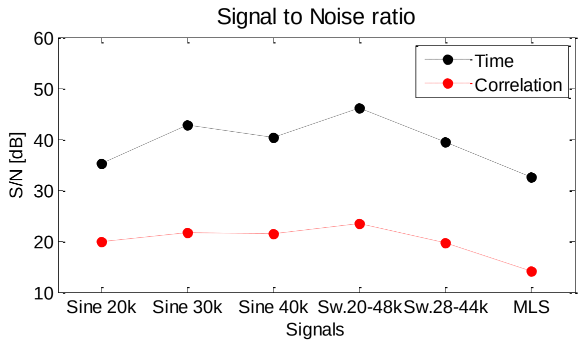

Figure 10. S/N ratio both in cross-correlation and time domain method.

Figure 10 shows that using the cross-correlation method is possible to obtain accurately the signal amplitude and getting an increase of between 15 and 20 dB in the S/N ratio, with a consequent improvement in the acoustic detection.

5. CONCLUSIONS

The acoustic beacon developed satisfies all the requirements for the KM3NeT-LBL acoustic positioning system. The beacon works properly in terms of functionality, matching, operation modes, signal configuration and power emission. The tests and calibration performed show stable and favourable results.
From the study of the signal processing technics with the analysis realized from the different measures performed in situ, we can conclude that by using the cross-correlation method with broadband signals (sweeps and MLS) the signal detection is optimized; it enlarges the S/N ratio improving the arrival time detection and its accuracy.

6. ACKNOWLEDGEMENTS

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