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Ultrasonic transmitter for positioning of the large underwater neutrino telescope KM3NeT.

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Abstract

Underwater ultrasonic transducers are commonly used for marine applications including communication and positioning systems. In this work, an ultrasonic transmitter transducer developed for the very large underwater neutrino telescope KM3NeT positioning is presented. The telescope infrastructure will have some degree of motion due to sea current; hence a positioning system is needed in order to monitor the position of the optical sensors. For this purpose, a reliable and affordable positioning based on acoustic systems is used. The ultrasound transmitter prototype developed as part of the positioning system is composed of a commercial FFR transducer and specifically designed electronics to optimize the system and fulfil the requirements of the KM3NeT infrastructure. The transmitter is able to generate high-power short signals with arbitrary waveform in a range of 20 kHz - 40 kHz and withstand high pressures. Signal processing techniques such as advanced cross-correlation methods and filtering as well as broad-band ultrasound signals are also applied for optimizing the acoustic emission and position detection. The work done for a precise laboratory testing and optimization of the system is described. The prototype has been integrated in the ANTARES neutrino telescope for testing its accuracy and the reach in situ. The test results obtained are also presented in this communication.

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1. Introduction

The use of sound in water is interesting for many applications, since low frequency sound signals travel along water with very low attenuation. During last decades, acoustic transducers have been developed for underwater uses such as communications, bioacoustics, particle detection, positioning systems, etc. The design of acoustic systems

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has been developed specifically for each application since the requirements are diverse. Nowadays, these designs are still under investigation since the needs become different and this requires improvement of previous designs.

The group of Acoustics applied to astroparticle detection from the Universitat Politècnica de València collaborates with two underwater neutrino telescopes: ANTARES (Ageron et al., 2011) and KM3NeT (KM3NeT Technical Design Report, 2010). Acoustic and signal processing technologies are developed and studied for tasks in positioning and calibration of such detectors.

An ultrasonic transmitter prototype has been developed for the monitoring of the optical sensors placed along the detection lines of the underwater telescope KM3NeT. Nowadays, the KM3NeT project is in its first construction phase, after the preparatory and design phases. The detection lines are anchored in the sea bottom and are held vertical by buoys in their top. Due to the sea current, the lines (and the sensors) have some motion. However, for this application, the optical module positions need to be well determined in order to reconstruct the neutrino direction after its interaction with the media sea. For this purpose, an accurate positioning system linked to the telescope elements is needed. The distances from acoustic emitters and receivers of the line are of the km order, so acoustic signals emitted suffer a considerable attenuation.

The ability of the acoustic positioning system (APS) is measured in terms of accuracy, coverage and reliability. For this purpose, the ultrasonic transmitter has to be able to produce high power signals in the range of 20-40 kHz, withstand pressures up to 400 bars and accomplish some requirements attending to the specifications for the APS of the telescope. The developed prototype is composed of a commercial Free Flooded Ring (FFR) transducer and specifically designed electronics to optimize the system and fulfil the requirements of the KM3NeT infrastructure.

Two of the acoustic transmitter prototypes have been integrated in the ANTARES (Arid, 2009) and NEMO/SMO (Viola et al., 2013) acoustic systems and are being tested. The results of the tests performed in situ will be shown in this paper.

2. Ultrasonic transmitter for the APS

The acoustic positioning system (APS) of KM3NeT provides the required information during the deployment and operation phases of the telescope. During the implementation phase, the APS must provide the position of the mechanical operation phase of the telescope, APS data are used to retrieve the positions of the optical modules (OMs) with an accuracy of about 10 cm. The positioning is based on a Long-Baseline (LBL) reference system consisting of acoustic transceivers distributed on the sea bottom at known positions and acoustic receivers (hydrophones) placed at the storeys of the detection lines. In addition, there will be compass-tiltmeters devices to measure the orientation and computers on-shore for data handling and analysis. The hydrophone positions are determined by measuring acoustic travel time between the emission and the arrival of the receiving signal at the hydrophones. By triangulation method, obtaining the travel time from at least three acoustic travel times per hydrophone, the position can be determined.

The ultrasonic transmitter prototype for the APS of KM3NeT (Larosa et al., 2013, Larosa, 2012, Llorens et al., 2012, Arid, 2012) consists of a SX30 FFR transducer from Sensortech Ltd. (Canada) and an especially designed Sound Emission Board (SEB) which adapts and amplifies the transducer, as well as, accomplishes all the functionalities required by KM3NeT. The transmitting power achieved with these first prototypes is 173 dB (re 1µPa@1m) for 35 kHz frequency (bottom, middle and right panels of Fig. 1).

2.1. Ultrasonic transducer FFR SX30

The FFR SX30 is an efficient transducer that provides reasonable power level over wide range of frequencies and deep ocean capability. According to the manufacturer they work in the 20 kHz - 40 kHz frequency range; they have unlimited depth for operation (tested up to 440 bars) with a transmitting and receiving voltage response of 133 dB re 1µPa/V at 1m. These transducers are simple radiators and have omnidirectional directivity pattern in the plan perpendicular to the axis of the ring, while in the planes containing the axis there is a minimum (reduction of about 5 dB) of sensitivity responses at 60º.

The transducer has been moulded in order to adapt it to the mechanical holding and have a better protection. The bottom left panel of Fig.1shows the pattern sensitivity per frequency has very low variation respect to the nude transducer pattern; the sensitivity is reduced by 1 dB - 2 dB for some frequencies.

2.2. Sound emission board (SEB)

The design of the SEB fulfils the requirements and specifications for the APS system of KM3NeT (Llorens et al., 2012). For instance, it has to be operational for long time in the deep sea that is, in an inaccessible location and under high pressure. Besides, it has to provide short, high-power signals generated with limited electrical power supply (about 1 W) and handle all the communication processes for configuration, triggering, etc.

The SEB has been designed for low-power consumption and it is adapted to the neutrino infrastructure using power supplies of 12 V and 5 V with a consumption of 1 mA and 100 mA, respectively. It is able to emit arbitrary intense short signals based on the Pulse-Width Modulation technique. The communication of the board with the PC is established with the standard protocol RS-232 through a RS-485 adapter on the board.

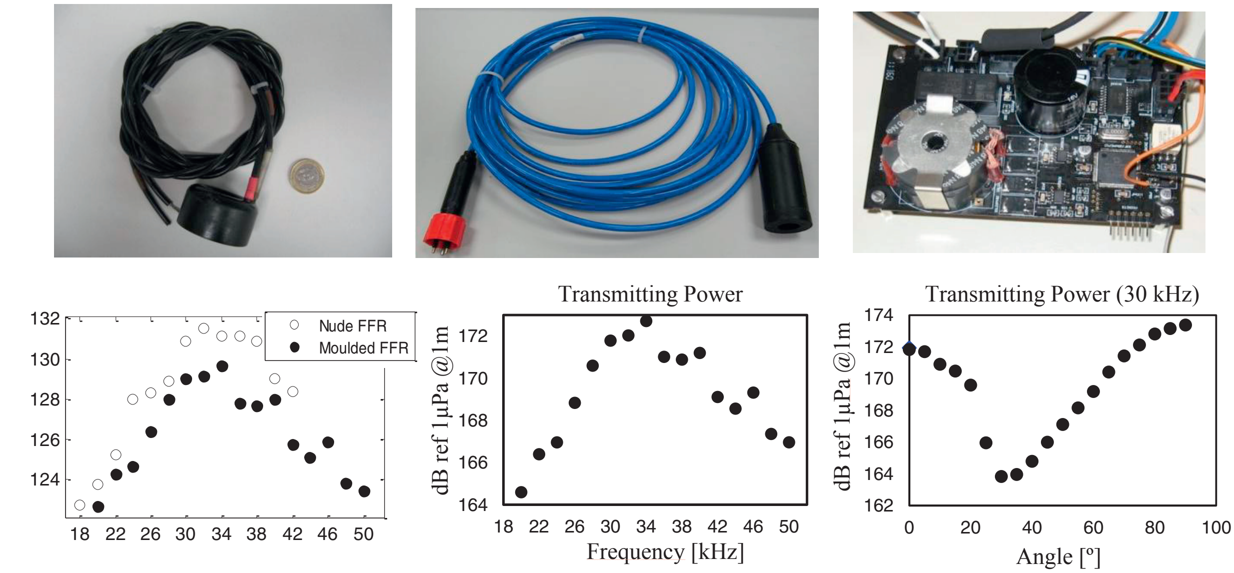


Fig.1 On top, view of the Free Flooded Ring transducer without over-moulding (left) and with (middle) and the Sound Emission Board (right). On bottom, Transmitting Voltage Response of the transducer in function of frequency (left), Transmitting Power (versus frequency in middle and versus angle in right).

3. Analysis methods and Results

3.1. Detection Strategy

The elaboration of protocols and analysis processing techniques are necessary for the correct detection of the signals used in these tasks. 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 of the signal received in time domain for the sine signals and the cross-correlation method of the received signal for the broadband signals used, such as sine sweep signal; it is a sinusoidal signal, which frequency is continuously varied from a starting frequency up to an end frequency, covering the frequency range of interest. As well, maximum length sequence (MLS) signal is used with the correlation method; this signal is a pseudorandom binary sequence with a flat spectrum.

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 on the frequency of the emitted signal. The left graphic of Fig. 2 shows an example of one received sine signal of 40 kHz and its envelope.

The cross-correlation method determines the arrival time of the received signal by taking the interval of time corresponded 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 they are easier to discern than others peaks. The middle graphic of Fig. 2 shows an example of cross-correlation method for received sine sweep signal from 28 kHz to 44 kHz and the right graphic shows an example of cross-correlation method for received MLS signal.

The cross-correlation method gives advantages in terms of accuracy in the time detection and improves the efficiency of the detection time and the signal to noise ratio (S/N). Besides, it has better echoes discernment.

3.2. In situ test results

In situ tests with the ultrasonic transmitter prototypes have been performed within the neutrino telescope infrastructures installed in Capo Passero and ANTARES site. The signals emitted in the tests were: three sine signals of 20 kHz, 30 kHz and 40 kHz, two sine sweep signals from 20 kHz to 48 kHz and from 28 kHz to 44 kHz, and a MLS signals.

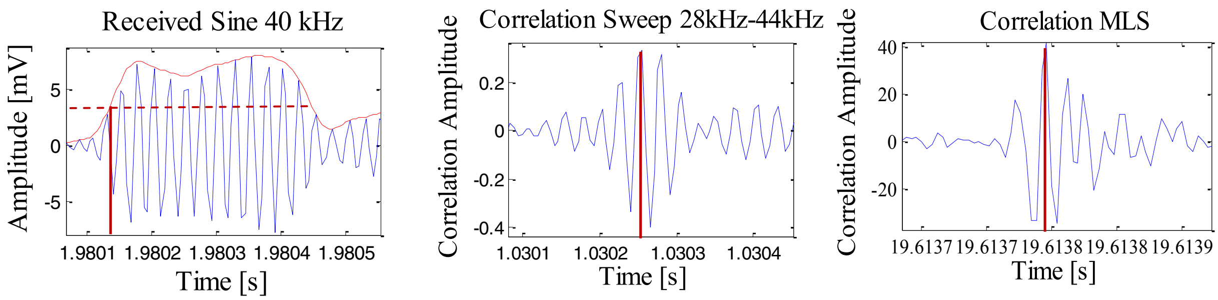


Fig.2 Examples of: received sine signal of 40 kHz with envelope (left), cross-correlation of received sine sweep signal from 28 kHz to 44 kHz (middle) and cross-correlation of received MLS signal (right).

The received signals have been analysed with the methods described before in order to know the Time of Arrival (ToA) variation stability, and the pressure amplitude reach. Data recorded in ANTARES test (2500 m depth) was taken by a hydrophone at a distance of 410 m from emitter. Concerning the emitted signals, they were sent in sequences of 20 pulses. As an example of the received signals during the test, Fig. 3 shows a sine sweep signal sequence recorded during the test performed and its cross-correlation. It shows that working in the cross-correlation domain the amplitude of the signal increases by two orders of magnitude, with a consequent improvement in the acoustic detection.

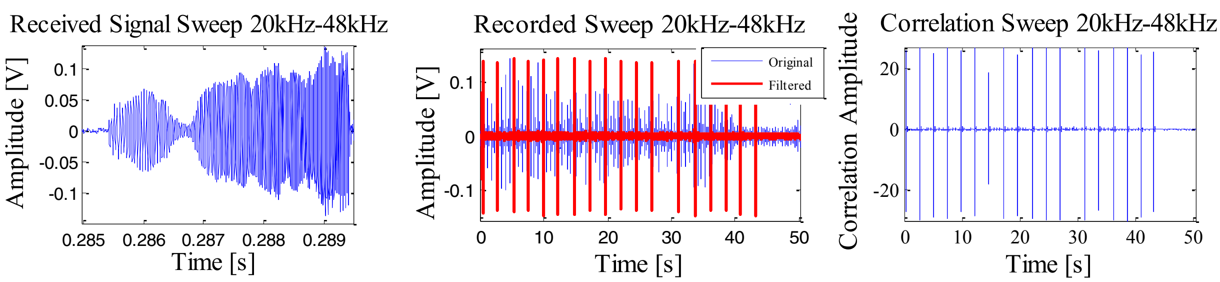
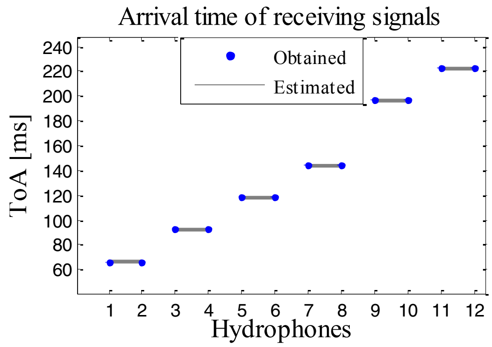


Fig.3 Example of sine sweep signal from 20 kHz to 48 kHz: a single received (left), recorded (middle) and correlation (right).

The data recorded in NEMO tower test (3500 m depth) was taken by hydrophones from all floors of the tower on which base the emitter is located. 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. Concerning the emissions, every kind of signal was emitted in sequences of 8 pulses.

As an example of the ToA obtained at the NEMO test, Fig. 4 shows the ToA obtained from the sine sweep signal from 20 kHz to 48 kHz applying the cross-correlation method. Supposing that the sound speed is 1500 m/s, match with the estimated distances from the emitter to the hydrophones along the line. Table 1 shows the stability of the ToA values obtained from all hydrophones per signal, the standard deviation of the ToA distribution varies from 29 µs and 65 µs with the threshold method and 27µs and 103 µs with the correlation method.



	THRESHOLD METHOD	CORRELATION METHOD
TYPE of 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 20kHz -48kHz		0.027

The signals received in the ANTARES test performed have been propagated in simulations to further distances (up to 2.16 km) in order to know the pressure levels reached and the amplitude signal received by the hydrophones and its correlation amplitude. The signals received are propagated applying the spherical divergence loss transmission and the sea water absorption coefficient per frequency. The pressure amplitude of the acoustic signals emitted by the FFR+SEB prototype as a function of the distance is shown in the left plot of Fig. 5. It has been determined for 20 kHz and 40 kHz tone bursts, and sine sweeps (20 kHz to 48 kHz range). The acoustic pressure values at 1 km from source are between 33 mPa and 46 mPa, depending on frequency. At 1.5 km the pressure values are between 22 mPa and 25 mPa. These signals could be detected by the ANTARES receivers since they can detect signal pressure amplitudes of 20 mPa under calm sea conditions. The signals sent by the emitter at 2160 m of distance from source do not reach the minimum detection levels, which are between 10 mPa and 13 mPa, depending on frequency.

The signal to noise ratio (S/N) of the acoustic received signal propagated is shown in the right plot of Fig. 5. There is a favourable signal to noise relation for the acoustic signal up to about 1 km.

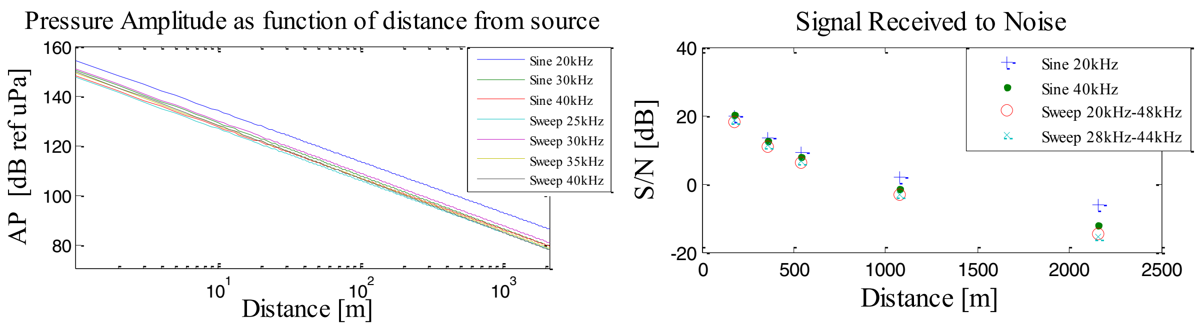


Fig.5 Pressure amplitude emitted by the acoustic transmitter FFR SX30+SEB per distance (left). On the right, the signal to noise ratio (dB) per signal under sea water conditions of ANTARES site.

Finally, in order to determine the reach of the system in terms of time detection accuracy, propagated signals have been introduced in 100 random (but known positions) of noise recorded. We have studied the ability of detecting them as a function of the distance (from 180 m to 2.16 km) using the correlation method. The values of deviation time (mean and sigma) for the detected signal with respect the true time are shown in Fig. 6. The obtained results show that the sweep signal can be detected at a distance of 2.16 km with good accuracy. Notice, that even if the signal to noise ratio is not favourable, it is possible to detect the signals emitted up to a 2.16 km with reasonable accuracy by using the detection signal technique describe above.

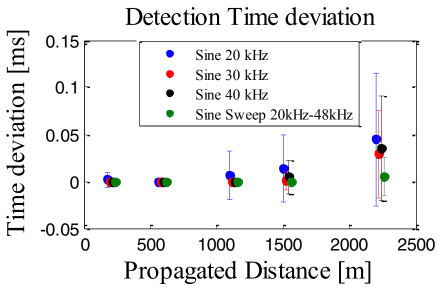


Fig.6 Values of deviation time (mean and sigma), with respect the true time, for the detected propagated signal with noise. It is determined by the correlation detection method.

4. Conclusion

The acoustic transmitter prototype developed satisfies the requirements for the acoustic positioning system of KM3NeT. It works as expected in terms of operation and power emission. 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. In particular, the case of the sine sweep signal using correlation method gives 27µs of stability. Simulations of propagation of these signals in the same conditions of the test show that they could be detected up to 2.16 km with good accuracy, which can be considered as a favourable reach for a large telescope such as KM3NeT. With this, we can conclude that the signal processing technique applied optimizes the signal detection and provide more accuracy in determining the signal arrival time.

Acknowledgements

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