NEMO-SMO acoustic array: a deep-sea test of a novel acoustic positioning system for a km^3-scale underwater neutrino telescope

S. Viola for the NEMO and SMO Collaborations[a,b], M. Ardid[c], V. Bertin[d], A. Enzenhöfer[e], P. Keller[d], R. Lahmann[e], G. Larosa[c], C.D. Llorens[c]

[a] *INFN-Laboratori Nazionali del Sud, Via S. Sofia 62 I-95125, Catania, Italy*
[b] *Università degli Studi di Catania, Via S. Sofia 64 I-95125, Catania, Italy*
[c] *Institut d' Investigació per a la Gestiò Integrada de Zones Costaneres - Universitat Politèctnica de València (UPV), C/Paranimf 1, 46730 Gandia, València, Spain*
[d] *CPPM, CNRS/IN2P3 et Universite de la Mediterranee, 163, Avenue de Luminy, Case 902, 13288 Marseille Cedex 9, France*
[e] *Universität Erlangen ECAP (Erlangen Centre for Astroparticle Physics), Erwin Rommel Str. 1, 91058 Erlangen,Germany*

Abstract

Within the activities of the NEMO project, the installation of a 8-floors tower (NEMO-Phase II) at a depth of 3500 m is foreseen in 2012. The tower will be installed about 80 km off-shore Capo Passero, in Sicily. On board the NEMO tower, an array of 18 acoustic sensors will be installed, permitting acoustic detection of biological sources, studies for acoustic neutrino detection and primarily acoustic positioning of the underwater structures. For the latter purpose, the sensors register acoustic signals emitted by five acoustic beacons anchored on the sea-floor. The data acquisition system of the acoustic sensors is fully integrated with the detector data transport system and is based on an "all data to shore" philosophy. Signals coming from hydrophones are continuously sampled underwater at 192kHz/24 bit and transmitted to shore through an electro-optical cable for real-time analysis. A novel technology for underwater GPS time-stamping of data has been implemented and tested. The operation of the acoustic array will permit long term test of sensors and electronics technologies that are proposed for the acoustic positioning system of KM3NeT.

Keywords: acoustic positioning, neutrino telescope, GPS time, acoustic tracking

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1. Introduction

The acoustic positioning system is a mandatory sub-system of an underwater neutrino telescope. In such a detector, the arrival direction of neutrinos is reconstructed by detecting the Cherenkov light emitted by secondary muons, generated in the charged current interactions of neutrinos with the nucleons within the effective volume of the detector [1]. The Cherenkov light is detected by means of an array of optical sensors installed on underwater structures, anchored to the sea-floor and kept vertical by a submerged buoy at top. The upper parts of the structures move under the influences of the sea current. In order to reconstruct the muon direction with an accuracy of a few tenths of a degree, the position of each optical sensor has to be known with an accuracy of better than 20 cm [2]. Typically, the underwater positioning is performed by means of acoustic beacons, anchored in known positions, and an array of acoustic sensors installed in the mechanical structures to be positioned. The position of each acoustic sensor with respect to the reference system of the beacons is calculated by the time of flight (TOF) of the acoustic waves between the emission by each beacon and the arrival at each sensor.

2. The NEMO-SMO positioning system

An innovative positioning system for an underwater km^3-scale neutrino telescope will be installed and tested in the deep sea in the framework of the SMO (Submarine Multidisciplinary Observatory) project within the NEMO Collaboration activities [3]. The project aims at the construction, integration and joint operation of a submarine large bandwidth acoustic antenna that will be installed on board the NEMO-Phase II demonstrator. The demonstrator, that will be installed in 2012 off-shore Capo Passero (South-East Sicily) at a depth of 3500 m, is a prototype of a neutrino telescope's detection unit. The prototype, about 400 m high, is composed of a vertical sequence of 8 horizontal aluminum structures 8 m long, called "floors", interconnected by a system of dyneema ropes. The vertical distance between two adjacent floors is 40 m. A spacing of about 100 m is added between the first floor and the base of the tower to allow for a sufficient water volume below the detector. The positioning of the detector is provided by a 3D array of 18 acoustic sensors, installed on both ends of each floor and on the base of the detector (monitoring station). The position of each sensor is calculated with respect to a reference system composed of 4 autonomous acoustic beacons, anchored on the sea-bed at about 500 m from the base of the detector, and one additional beacon, located at the base of the detector and connected with the power electronics of the tower. Their absolute positions and relative distances will be determined, acoustically, during the detector deployment operations using a ROV (Remotely Operated Vehicle) equipped with a USBL (ultra-short baseline) positioning system. The accuracy on the positioning of the beacons on the seabed is about 1 m. In the NEMO-SMO project autonomous acoustic beacons manufactured by ACSA [4] will be employed. Each beacon transmits its own TSSC (Time Spectral Spread Codes) sequence, that is a pattern of 6 pseudo-random pulses (spaced by ~1 s) with a period of about 6 s. Each sequence is different from the others. The beacon pulse is a 32 kHz sinusoidal wave, 5 ms long. The amplitude is 180 dB re μPa at 1 m. Once the distances between the beacons and the monitoring station, at the tower base, have been determined by the ROV, the time of emission of the beacon pulses is obtained by measuring the time of arrival of the pulses at the monitoring station. The sound velocity in the site is evaluated by using pressure, temperature and salinity values, measured with two CTD (Conductivity, Temperature, Depth) profilers installed on the first and on the last floor of the detector. The CTD used is a 37-SM MicroCAT CTD, manufactured by Sea Bird [5]. The array of the acoustic receivers of the NEMO-SMO project is composed of: 14 high sensitivity and broadband (10 Hz-70 kHz) hydrophones SMID TR-401 [6], provided by INFN [7]; 2 free flooded rings hydrophones Sensor Technology Ltd SX-30, provided by UPV [8] in collaboration with CPPM-CNRS [9], suggested for possible use as transceiver for the KM3NeT positioning system [10]; 2 custom piezo-sensors developed by ECAP [11] that will be installed in special Opto-Acoustic Modules [12].

3. The NEMO-SMO data acquisition system

The data acquisition system of the SMO acoustic array is fully integrated into that of the NEMO Phase II detector. Unlike the previous acoustic positioning systems developed for NEMO Phase I [13] and ANTARES [14] detectors, in NEMO-SMO the recognition and the analysis of the acoustic signals emitted by the beacons is entirely performed on-shore thanks to an acquisition system based on an “all data to shore” philosophy [15]. All acoustic signals acquired by the acoustic sensors are sampled underwater and continuously sent to shore through an electro-optical cable that connects the NEMO-SMO detector to the shore-station. A schematic view of the data acquisition system for a single floor of the NEMO-SMO detector is shown in Figure 1. For each acquisition channel of the array, the signals from the acoustic sensor and its respective preamplifier are digitized underwater by a dedicated board called “AcouBoard”. The AcouBoard hosts a professional stereo audio ADC 192kHz/24bit and a AES/EBU stereo compliant DIT (Digital Interface Transmitter). The use of standard protocols allows to manage the audio data with professional sound boards and commercial software reducing the costs with respect to custom protocols. All AcouBoards are driven by the same master clock, driven by a common on-shore GPS station (Symmetricon XLi). The master clock signal is embedded into a serial synchronous data stream and transmitted to the detector through the main electro-optical cable of the NEMO-SMO detector. Thanks to a novel technology for underwater GPS timestamping of the data, implemented by the NEMO and SMO Collaborations, all digital audio data are labelled off-shore with the absolute GPS time of acquisition [17]; for each floor of the detector a floor control module (FCM) collects the data coming from the underwater sensors (acoustic sensors, optical sensors and environmental probes), adds a time label and sends them to shore via optical link. The resolution of the time labelling is 25 ns. On shore, the audio data are parsed by a board, called eFCM (Ethernet Floor Control Module) that addresses them via TCP/IP protocol to a local computer network for signal recognition, analysis and storage. Following the recent refurbishment of the INFN-LNS Capo Passero infrastructure, NEMO-SMO will be the first cabled large bandwidth acoustic array deployed at 3500 m depth and it will be fully connected via optical fibre to the GARR (Italian Consortium for Research Network) backbone [16].

4. Test and characterization of the NEMO-SMO array

The performances of the NEMO-SMO array has been evaluated at INFN-LNS, where a test bench has been set up. The test bench included the whole data acquisition chain of a single NEMO-SMO floor. A 100 km long optical link has been employed to simulate the data transmission on the underwater electro-optical cable. Since the data acquisition system of the NEMO-SMO detector is modular, the measurements related to the test floor can be extended to all floors of the detector. Intrinsic electronic noise of the data acquisition system has been measured. The total power of the electronic noise is about -72 dB re 1 V_{rms}. In Figure 2 the power spectral density of the intrinsic noise of the NEMO-SMO data acquisition chain is shown. In Figure 3 we report the electronic noise spectrum in equivalent acoustic pressure for the SMID TR-401 hydrophone, described in details in Section 5. For comparison the figure includes the expected background noise for different sea-state conditions. Since the positioning of the detector is based on precise measurement of the time of arrival (ToA) of the acoustic signals emitted by the beacons at the acoustic sensors, a characterization of the timing performances of the data acquisition system has been done as well. The accuracy of measurement of the ToA depends on the accuracy of the latency time of the data acquisition electronics. For positioning purposes it must be known and fixed. The latency time of the underwater electronics has been measured by sending an electrical test signal to the input of the digitization board (AcouBoard) at a known time. The time difference between the underwater time-stamping of the data and the time of emission of the test signal represents the latency time of the data acquisition electronics. The setup used for this measurements is sketched in Figure 4. As test signal, a 208.4 μs long sinusoidal electrical wave with a frequency of 24 kHz has been used, produced by a waveform generator AGILENT 33220A. The emission has been triggered by a TTL pulse emitted by the FCM that is remotely driven by means of the control software of the detector. The software provides the emission time of the trigger pulse with an accuracy of 100 ps. The audio data, labelled with the GPS time by the FCM, have been acquired by a professional AES/EBU sound card (model RME HDSP AES-32) and analyzed off-line by means of dedicated MATLAB codes developed by the SMO Collaboration. For the analysis, the data have been upsampled to 192 MHz and correlated with the expected test signal by means of a cross correlation function. The upsampling improves the time resolution

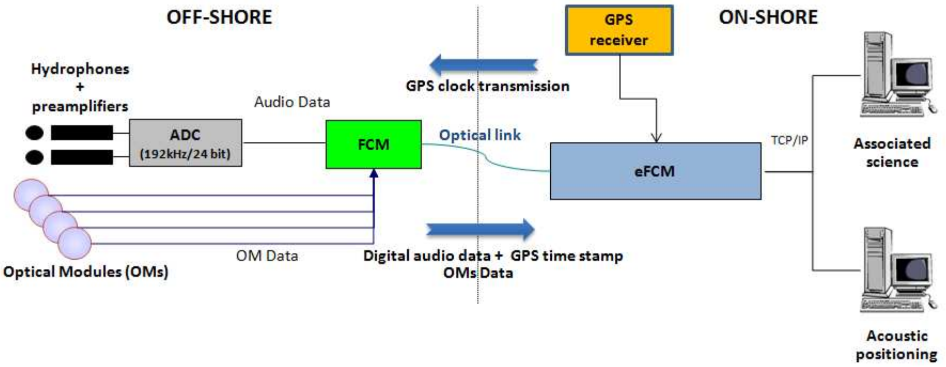

Figure 1: Data acquisition chain of a floor of the NEMO-SMO detector. The signals from hydrophones are sampled off-shore, time labelled and continuously sent to the shore station for real-time analysis.

of each measurement to about 5.2 ns. The time difference between the GPS time associated to the maximum amplitude of the cross-correlation function and the emission time has been calculated with a semi-automatic procedure. The whole system has been restarted before each acquisition. The preliminary value of the time latency is 39.4 μs ± 0.1 μs. This feature allows to calibrate the apparatus on-shore, before the deployment, with an overall accuracy compatible with the accuracy requested by the KM3NeT Consortium for the acoustic positioning of the Optical Modules (OMs) [2].

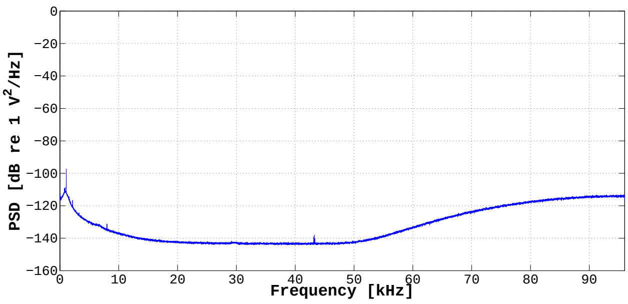

Figure 2: Power spectral density of the intrinsic electric noise of the NEMO-SMO data acquisition system.

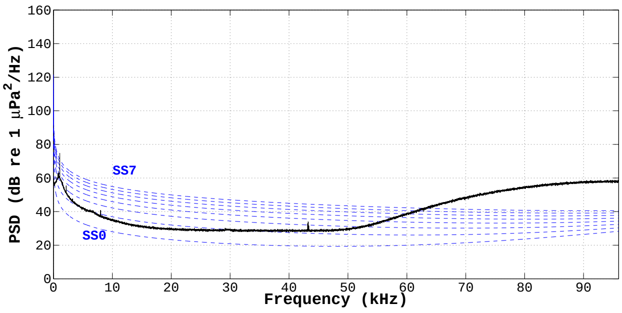

Figure 3: Power spectral density of the intrinsic electric noise of the NEMO-SMO data acquisition system in equivalent acoustic pressure for the SMID TR-401 hydrophone (solid black line). The dotted blue lines represent the expected background acoustic noise for different sea-state conditions.

5. Integration and tests of acoustic sensors

As elaborated at the end of Sec. 3, three different types of acoustic sensors are employed in the NEMO-SMO array. The SMID sensors and their respective preamplifiers SMID AM-401 (gain +38 dB) have been characterized and tested at the NATO Undersea Research Centre of La Spezia (Italy). The SMID hydrophones feature an overall sensitivity of -172±3 dB re 1 V/μPa in a large frequency range (10 Hz-70 kHz). Moreover, the change of sensitivity as a function of pressure is less than 1 dB [15]. The performances of the free flooded ring hydrophones installed in the NEMO-SMO array have been evaluated by UPV. Their sensitivity is -193 dB re 1 V/μPa in the range 20 kHz-40 kHz. Tests performed at INFN-LNS have demonstrated the full compatibility of the sensors with the SMID AM-401 preamplifier. In order to evaluate and compare the performances in water of the two hydrophone models, tests in a water pool have been performed at IDASC (Istituto di Acustica e Sensoristica “Orso Mario Corbino”) [18] in Rome. The hydrophones have been characterized using a calibrated emitter ITC 1032 [19]. The hydrophones have been placed at known distances from the acoustic source by means of mechanical supports (see Figure 5) and connected to the data acquisition system of the detector. The data analysis of the measurements in water is in progress. Moreover, integration tests of the custom piezo-sensors for the Opto-Acoustic Module with the NEMO-SMO data acquisition system have been performed at LNS. The piezo-sensors have been already installed into the Opto-Acoustic Modules. In Figure 6 a piezo-sensor and its respective preamplifier board inside the Opto-Acoustic Module are shown.

6. Conclusion and perspectives

The NEMO-SMO array will be completely operative in the first months of 2012. It will allow to test sensors and electronics for a possible positioning system for KM3NeT. In measurement performed at INFN-LNS, the latency of the data acquisition and transport system was determined with an overall accuracy of better than 1 μs, as requested by the KM3NeT Consortium. Since the raw data of the hydrophones will be contin-

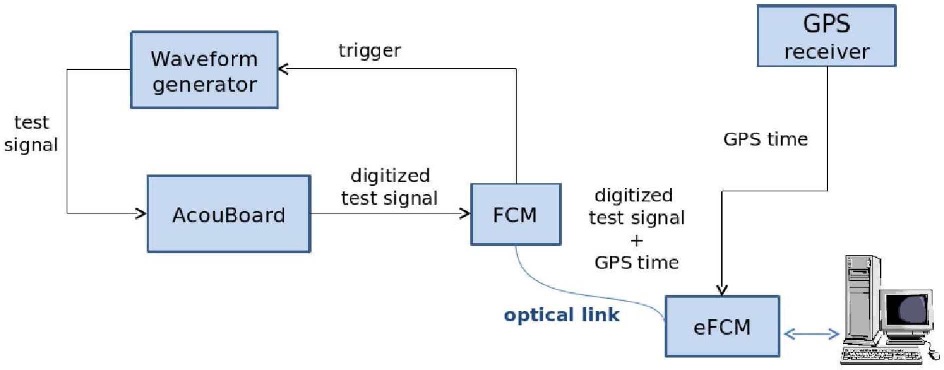

Figure 4: Schematic view of the experimental setup used for the time latency measurement of the SMO acquisition electronics.

uously transmitted to shore, SMO data will be available also for other applications, such as real-time acoustic monitoring of the installation site in a range of several tens of km. The audio data will be used as input for simulations on neutrinos acoustic detection [20] at the Capo Passero Site, one of the candidate sites for KM3NeT. For this purpose, DSP techniques based on matched filters will be tested to improve source identification and localization. Moreover, as demonstrated by the successful operation of the NEMO-OνDE detector [21], hydrophone data will be an excellent tool for passive detection and tracking of cetaceans over a long time interval and for the study of acoustic noise variations, as a function of time, in the Mediterranean Sea [22]. Acoustic data will be also used in activities addressing the long term monitoring of geophysical phenomena (e.g. tsunami acoustic signals) [23].

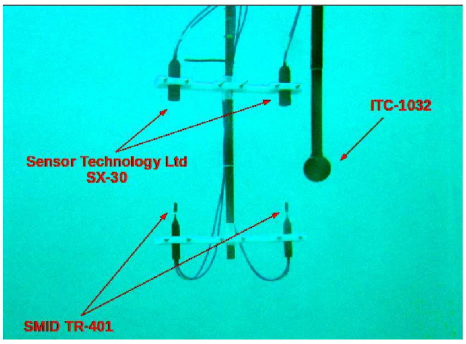

Figure 5: Experimental setup for the acoustic measurements in water at the IDASC water pool.

7. Acknowledgements

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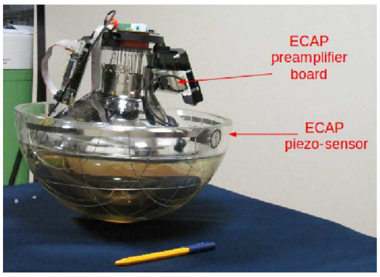

Figure 6: Piezo-sensor and preamplifier board integrated in an Opto-Acoustic Module.