Status of NEMO: results from the NEMO Phase-1 detector

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The NEMO Collaboration installed an underwater detector including most of the critical elements of a possible km\textsuperscript{3} neutrino telescope: a four-floor tower (called Mini-Tower) and a Junction Box, including the data transmission, the power distribution, the timing calibration and the acoustic positioning systems. These technical solutions will be evaluated, among others proposed for the construction of the km\textsuperscript{3} detector, within the KM3NeT Consortium. The main test of this test experiment was the validation of the proposed design solutions mentioned above. We present results of the analysis of data collected with the NEMO Mini-Tower. The position of PMTs is determined through the acoustic position system; signals detected with PMTs are used to reconstruct the tracks of atmospheric muons. The angular distribution of atmospheric muons was measured and results were compared with Monte Carlo simulations.

1. INTRODUCTION

Due to the expectations on neutrino fluxes from galactic and extragalactic sources, mainly based on the measured cosmic ray fluxes and the estimated fluxes from theoretical models \cite{1}, the opening of the high-energy neutrino astronomy era can only be made with detectors of km\textsuperscript{3} scale.

The activity of the NEMO Collaboration was mainly focused on the search and characterization of an optimal site for the detector installation and on the development of key technologies for the km\textsuperscript{3} underwater telescope to be installed in the Mediterranean Sea.

A deep sea site with optimal features in terms of depth and water optical properties has been identified at a depth of 3500 m about 80 km off-shore Capo Passero (Southern cape of Sicily). A long term monitoring of the site has been carried out \cite{2}.

One of the efforts undertaken by the NEMO Collaboration has also been the definition of a feasibility study of the km\textsuperscript{3} detector, which included the analysis of all the construction and installation issues and the optimization of the detector geometry by means of numerical simulations.

The technical solutions, proposed by the NEMO Collaboration, will be evaluated, among others proposed for the construction of the km\textsuperscript{3} detector, within the KM3Net Consortium \cite{3}. As an intermediate step towards the construction of the underwater km\textsuperscript{3} detector and to ensure an adequate process of validation, the NEMO Collaboration built a technological demonstrator and installed off-shore the port of Catania (Sicily). The project, called NEMO Phase-1, has allowed test and qualification of the key technological elements (mechanics, electronics, data transmission, power distribution, acoustic positioning and time calibration system) proposed for the km\textsuperscript{3} detector \cite{4}. After a brief description of the detector lay-out, we describe the atmospheric muon data analysis procedure and present the results. In particular, the atmospheric muon angular distribution was measured and compared with Monte Carlo simulations.

The NEMO Collaboration is also constructing an underwater infrastructure at the Capo Passero site (NEMO Phase-2). The main goal of this project is to finally validate the technologies proposed for the realization and installation at the depths needed for the km\textsuperscript{3} detector. The status of NEMO Phase-2 is also presented.

2. THE NEMO PHASE-1 DETECTOR

The apparatus includes prototypes of the critical elements of the proposed km\textsuperscript{3} detector \cite{4}: the Junction Box (JB) and four floor NEMO Tower (the Mini-Tower), as sketched in Figure \cite{4}.
2.1. The Junction Box

The JB is a key element of the detector. It must provide connection between the main electro-optical cable and the detector structures and has been designed to host and protect from the effects of corrosion and pressure the opto-electronic boards dedicated to the distribution and the control of the power supply and digitized signals.

The NEMO Phase-1 JB has been built following the concept of double containment. Pressure resistant steel vessels are hosted inside a large fiberglass container. This last one is filled with silicon oil and pressure compensated. This solution has the advantage to decouple the two problems of pressure and corrosion resistance.

Moreover, all the electronics components that were proven able to withstand high pressure were installed directly in the oil bath.

2.2. The Mini-Tower

The Mini-Tower is a prototype of the NEMO Tower [5]. It is a three dimensional flexible structure composed by a sequence of four floors interlinked by cables and anchored on the seabed. The structure is kept vertical by appropriate buoyancy on the top.

Each floor is made with a 15 m long structure hosting two photomultipliers (PMTs) (one down-looking and one horizontally looking) at each end (4 PMTs per storey). Besides, each floor is connected to the following one by means of four ropes that are fastened in a way that forces each floor to take an orientation perpendicular with respect to the adjacent (top and bottom) ones. The floors are vertically spaced by 40 m. An additional spacing of 150 m is added at the base of the tower, between the tower base and the lowermost floor to allow for a sufficient water volume below the detector.

In addition to the 16 PMTs the instrumentation installed on the Mini-Tower includes several sensors for calibration and environmental monitoring, such as oceanographic instrumentation to measure water current (ADCP), water transparency (C*), sea water properties (CTD), and a pair of hydrophones (H) for acoustic positioning. A scheme of the fully equipped Mini-Tower is shown in Fig. 2.

Figure 2. Fully equipped NEMO Mini-Tower pictorial view (see text in sec. 2.2 and 4.1 for details.)
3. DETECTOR OPERATION

The NEMO Phase 1 detector was deployed in December 2006 (see Fig. 3). The apparatus was connected to the Underwater TestSite infrastructure of the Laboratori Nazionali del Sud, installed off shore Catania at a depth of about 2000 m.

![Figure 3. Pictures of the JB (top) and of the Mini-Tower (bottom) deployment.](image)

After 4 months, an attenuation in the optical fibers transmission was observed inside the JB. In May 2007, the JB was shut down because of a short-circuit. The JB was recovered in June 2007; it was repaired and re-installed in April 2008. It’s working since then. A poor manufacturing process caused a loss of buoyancy in the main buoy of the Mini-Tower and therefore a slow sinking of the whole tower.

Although these problems occurred during operations, the NEMO Phase-1 project successfully validated the key technologies proposed for the $\text{km}^3$ telescope, demonstrating also the NEMO Tower capability to detect and trace muons, as discussed in the following sections.

4. ATMOSPHERIC MUON DATA ACQUISITION

4.1. The data acquisition system

The PMT Front-End Module (FEM) was placed close to the PMT inside the glass sphere containing the optical module (OM). The FEM main goal is to acquire the analog signals produced by the PMT, encode and transmit these data to the Floor Control Module (FCM) (see Fig. 2). The hit pulse is sampled by two 8-bits Fast Analog to Digital Converters (Fast-ADC) running at 100 MHz but staggered by 5 ns.

The PMT signals, produced by the FEM boards, are collected by the FCM, packed together and transmitted through the optical link; control data are received from on-shore following the opposite direction. The on-shore host machine, called Floor Control Module Interface (FCMI), can be accessed through a Gigabit Ethernet (GbE) connection. The floor control module (FCM), roughly placed at the floor center, is powered by the floor power module (FPM) and connected to the Tower Base Module (TBM) through a fiber optic backbone. The TBM is connected through an inter-link cable to the JB and therefore to the on-shore lab. A detailed description of the Mini-Tower data acquisition and transport systems is given in [6].
4.2. The On-Line Trigger

The PMT raw data were sent by the FCM boards to the On-Line Trigger. The aim of this data processing was to select single time windows with a high probability to contain muon events. In this way most of the optical background was rejected, strongly reducing the data to be recorded.

The On-Line Trigger algorithm was based on searching the so called Simple Coincidences (SCs) among the hits. A SC is defined as a coincidence between 2 hits in 2 adjacent PMTs, placed at the same tower floor. The coincidence time delay was set to $\Delta T_{SC} \leq 20$ ns.

The trigger occurred when a SC was found. In this case, the On-Line Trigger stored all the hits recorded in a time window centered around the SC and long enough to contain the possible muon event. Two different values of the trigger time window were tested: 4 and 10 $\mu$s.

The event detection rate at the On-Line Trigger level ranges between 1.5 and 2 kHz. This value is consistent with hit coincidences induced by the measured optical background rate of 75-80 kHz [7]. The expected atmospheric muon trigger rate, evaluated from Monte Carlo simulations, is $\sim 1$ Hz. The signal is dominated by the noise and an Off-Line Trigger is therefore mandatory.

5. ATMOSPHERIC MUON DATA ANALYSIS

5.1. PMT data calibration

Before atmospheric muon data analysis could be started, the recorded PMT hits had to be decompressed and calibrated [5]. The hit wave-form is firstly re-sampled at 2 GHz (the ADC sampling is 200 MHz); the ADC channels are then decompressed and converted into amplitudes (in mV unit), using the decompression table generated during the FEM Boards characterization phase. The sample waveform rising edge is fitted with a sigmoid function and hit time is evaluated at the sigmoid inflection point. Time offsets provided by the time calibration system are finally added. At the end of the process the PMT hit waveform is reconstructed: the integral charge is determined with $\sigma \sim 0.3$ pC and converted in units of p.e. taking into account that 1 p.e. = 8 pC. The time is evaluated with an accuracy of $\sigma \sim 1$ ns.

5.2. The Off-Line Trigger

After the calibration procedure, the hit time estimate is 5 times better than the raw data level. For each event, the simple coincidences (SCs) were then re-calculated in order to reject the false SCs found by the On-Line Trigger. Besides, the new trigger seeds were calculated:

- Floor Coincidence (FC): a coincidence between 2 hits recorded at the opposite ends of a same storey ($\Delta T_{FC} \leq 200$ ns);
- Charge Shooting (CS): a hit exceeding a charge threshold of 2.5 p.e.

The ensemble of all hits participating to the Off-Line Trigger seeds was then analyzed. In particular, for each one we calculated the number of the other hits causality correlated according to the condition:

$$|dt| < dr/v + 20 \text{ ns},$$

where $|dt|$ is the absolute value of the time delay between the hits, $dr$ is the distance between the PMTs where the hits are detected, $v$ is the group velocity of light in seawater.

The maximum number of causality relations $N_{Caus}$ found in each event is then used to reject the background. In particular only the events having $N_{Caus} \geq 4$ were considered in the following steps.

5.3. The Causality Filter

Before trying any track reconstruction, it is mandatory to reject the background hits present inside the muon event.

In order to reduce the number of hits due to background the first step consists in the rejection of hits with amplitude smaller than 0.5 p.e. then a causality filter with respect to a reference hit is applied. The causality filter application proceeded in the following way.

The $N$ hits forming the event were sorted by time and the local frequency was calculated as:

$$f = \frac{N}{T_N - T_1},$$

where $T_N$ and $T_1$ are the times of the first and last events, respectively.
where $T_1$ and $T_N$ are respectively the occurrence time of the oldest and the youngest hits.

For each group of $n$ ($n = 5$) consecutive hits, we calculated the Poisson probability to detect $n$ background hits for an expected value of

$$n_{\text{exp}} = f \cdot \Delta T_g,$$

(3)

where $\Delta T_g$ is the time interval in which the $n$ hits were detected. The hit group with the minimum probability is likely to contain muon hits, instead of uncorrelated background hits.

The causality filter is then applied with respect to all hits in the group with the minimum probability. In particular for each reference hit, the number of hits among the $N$ forming the event and selected by the same condition in Eq. 1 are counted. Among the $n$ cases, the one that preserves the largest number of hits is chosen.

5.4. Muon track reconstruction

The hits surviving the causality filter were used to reconstruct the atmospheric muon tracks. The track reconstruction strategy used in this analysis is a robust track fitting procedure based on a maximum likelihood method. The algorithm takes into account the Čerenkov light features and the possible presence of unrejected background hits [9,10]. During the reconstruction procedure, the PMTs positions, reconstructed using acoustic positioning system data, were considered.

5.5. Results

A sample of data, recorded on 23rd-24th January 2007 when the tower was completely unfolded and corresponding to a livetime of 11.3 hours, was analyzed. A total of 3049 atmospheric muon events was reconstructed, corresponding to a mean reconstruction rate of 0.075 Hz, and their angular distribution was measured.

For comparison, a Monte Carlo simulation of the detector response to atmospheric muons was carried out. A total of $4 \cdot 10^7$ atmospheric muon events were simulated with MuPage [11], corresponding to a livetime of 11.3 hours. The detector response was simulated taking into account the light absorption length spectrum measured at the TestSite and the optical background evaluated from the measured PMT data. The Mini-Tower DAQ electronics and the On-Line Trigger were simulated. The detector geometry was simulated using the PMTs positions reconstructed using the acoustic positioning system data.

The angular distribution of reconstructed muon tracks, detected during the 23rd-24th January 2007 period, is shown in Fig. 4 together with the spectrum of the reconstruction likelihood. The figure reports also results from Monte Carlo simulations carried out for the same period, showing an excellent agreement.

Data recorded during the period between 2nd March and 12th April 2007 were also analyzed. At that time, the two lowest floors of the tower were already laying on the seabed. The corresponding livetime is 174.1 hours and the total number of reconstructed atmospheric muons is 27699 (reconstruction rate 0.044 Hz). The lower rate of reconstructed tracks is due to the smaller number of PMTs participating to the muon detection caused by the slow Mini-Tower sinking (see sec. 3).

6. NEMO PHASE-2

Although the Phase-1 project provided a fundamental test of the technologies proposed for the realization and installation of the detector, these must be finally validated at the depths needed for the km$^3$ detector. For these motivations the realization of an infrastructure on the site of Capo Passero has been undertaken. It consists of a 100 km cable, linking the 3500 m deep sea site to the shore, a shore station, located inside the harbor area of Portopalo of Capo Passero, and the underwater infrastructures needed to connect prototypes of the km$^3$ detector. At the same time a fully equipped 16 storey detection tower is under construction and will be installed on the Capo Passero site. With the completion of this project, foreseen by the spring of 2009, it will be possible to perform a full test at 3500 m of the deployment and connection procedures and at the same time set up a continuous long term on-line monitoring of the site properties (light transparency, optical background, water currents, ...) whose knowledge is essential for the installation of the full km$^3$ detector.

Due to the longer cable needed, with respect to
the Phase-1 project, the DC solution was chosen for the electro-optical cable power feeding. The main cable, manufactured by Alcatel, carries a single electrical conductor, that can be operated at 10 kV DC allowing a power transport of more than 50 kW, and 20 single mode optical fibres for data transmission. The DC/DC converter will be realized by Alcatel and will convert the high voltage coming from the shore into 400 V. The cable has been laid in July 2007. The cable deep sea termination, that includes the 10 kW DC/DC converter system, is presently under realization and will be deployed in the beginning of 2009.

7. CONCLUSIONS

The activities of the NEMO Collaboration progressed in the past two years with the realization and installation of the Phase-1 apparatus. With this apparatus it has been possible to test in deep sea the main technological solutions developed by the collaboration for the construction of a km$^3$ scale underwater neutrino telescope [2]. In particular the angular distribution of atmospheric muons was measured and results were compared with Monte Carlo simulations, finding an reasonable agreement. A Phase-2 project, which aims at the realization of a new infrastructure on the deep-sea site of Capo Passero at 3500 m depth, is presently progressing. After a careful revision of its design, following the experience gained with the Phase-1 project, the construction of a fully equipped 16 storey tower is under way. The tower will be installed and connected in spring of 2009.

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