Recent achievements of the NEMO project

E. Migneco\textsuperscript{a,\,*}, S. Aiello\textsuperscript{d}, A. Aloisio\textsuperscript{d}, F. Ameli\textsuperscript{i}, I. Amore\textsuperscript{a,\textdagger}, M. Anghinolfi\textsuperscript{a}, G. Barbarino\textsuperscript{a}, E. Barbarito\textsuperscript{b}, M. Battaglieri\textsuperscript{c}, M. Bazzotti\textsuperscript{i}, R. Bellotti\textsuperscript{i}, A. Bersani\textsuperscript{n}, N. Beverini\textsuperscript{p}, S. Biagi\textsuperscript{i}, M. Bonori\textsuperscript{d}, B. Bouhdaef\textsuperscript{p}, M. Brescia\textsuperscript{a,\textdagger}, G. Cacopardo\textsuperscript{a}, C. Cali\textsuperscript{a}, A. Capone\textsuperscript{a}, L. Caponetto\textsuperscript{m}, G. Carminati\textsuperscript{i}, B. Cassano\textsuperscript{b}, E. Castorina\textsuperscript{p}, A. Ceres\textsuperscript{b}, T. Chiarusi\textsuperscript{a}, M. Ciricella\textsuperscript{b}, R. Cocimano\textsuperscript{a}, R. Coniglione\textsuperscript{a}, M. Cordelli\textsuperscript{f}, M. Costa\textsuperscript{a}, A. D’Amico\textsuperscript{a}, C. D’Amato\textsuperscript{a}, V. D’Amato\textsuperscript{a}, G. De Bonis\textsuperscript{q}, G. De Rosa\textsuperscript{g}, G. De Ruvo\textsuperscript{b}, R. De Vita\textsuperscript{e}, C. Distefano\textsuperscript{a}, E. Falchini\textsuperscript{p}, V. Flaminio\textsuperscript{p}, K. Fratini\textsuperscript{e}, A. Gabrielli\textsuperscript{h}, S. Galeotti\textsuperscript{h}, E. Gandolfi\textsuperscript{f}, G. Giacomelli\textsuperscript{f}, F. Giorgi\textsuperscript{i}, G. Giovanetti\textsuperscript{a}, A. Grimaldi\textsuperscript{d}, A. Grmeka\textsuperscript{a}, R. Habel\textsuperscript{f}, E. Leonora\textsuperscript{m}, A. Lonardo\textsuperscript{j}, G. Longo\textsuperscript{o}, D. Lo Presti\textsuperscript{m}, F. Lucarelli\textsuperscript{q}, L. Maccione\textsuperscript{p}, A. Margiotta\textsuperscript{l}, A. Martin\textsuperscript{i}, R. Masullo\textsuperscript{q}, F. Maugeri\textsuperscript{a}, R. Megna\textsuperscript{b}, S. Minutoli\textsuperscript{e}, M. Mongelli\textsuperscript{b}, T. Montaruli\textsuperscript{k,\textdagger}, M. Morganti\textsuperscript{p}, P. Musico\textsuperscript{e}, M. Musumeci\textsuperscript{a}, C.A. Nicolau\textsuperscript{i}, A. Orlando\textsuperscript{a}, M. Osipenko\textsuperscript{e}, G. Osteria\textsuperscript{g}, R. Papaleo\textsuperscript{a}, V. Pappalardo\textsuperscript{a}, C. Petta\textsuperscript{d}, P. Piattelli\textsuperscript{d}, D. Piombo\textsuperscript{e}, G. Raia\textsuperscript{a}, N. Randazz\textsuperscript{o}, S. Reito\textsuperscript{d}, G. Ricco\textsuperscript{n}, G. Riccobene\textsuperscript{a}, M. Ripani\textsuperscript{e}, A. Rovelli\textsuperscript{a}, M. Ruppi\textsuperscript{b}, G.V. Russo\textsuperscript{m}, S. Russo\textsuperscript{o}, P. Sapienza\textsuperscript{a}, M. Sedita\textsuperscript{a}, E. Shirokov\textsuperscript{e}, F. Simeone\textsuperscript{q}, V. Sipala\textsuperscript{m}, C. Sollima\textsuperscript{p}, F. Speziale\textsuperscript{a}, M. Spurio\textsuperscript{i}, M. Taiti\textsuperscript{n}, G. Terreni\textsuperscript{h}, L. Trasatti\textsuperscript{f}, S. Urso\textsuperscript{d}, V. Valente\textsuperscript{f}, M. Vecchi\textsuperscript{q}, P. Vicini\textsuperscript{q}, R. Wischnewski\textsuperscript{i}

\textsuperscript{a}Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud, Via S. Sofia 62, 95123 Catania, Italy
\textsuperscript{b}INFN Sezione di Bari, Via E. Orabona 4, 70126 Bari, Italy
\textsuperscript{c}INFN Sezione di Bologna, Via Enrico Fermi 40, 40014 Frascati, Italy
\textsuperscript{d}INFN Sezione di Catania, Via S. Sofia 64, 95123 Catania, Italy
\textsuperscript{e}INFN Sezione di Genova, Via Dodecaneso 33, 16146 Genova, Italy
\textsuperscript{f}INFN Sezione di Napoli, Via Cintia, 80126 Napoli, Italy
\textsuperscript{g}INFN Sezione di Pisa, Polo Fibonacci, Largo B. Pontecorvo 3, 56127 Pisa, Italy
\textsuperscript{h}INFN Sezione di Roma 1, P.le A. Moro 2, 00185 Roma, Italy
\textsuperscript{i}Department of Physics, University of Wisconsin, Madison, WI 53711, USA

Available online 12 January 2008

\textsuperscript{\textdagger}Corresponding author.
\textit{E-mail address: migneco@lns.infn.it (E. Migneco).}

0168-9002/$ - see front matter \textcopyright 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2008.01.012
Abstract

The status of the activities towards the realization of a km$^3$ Cherenkov neutrino detector carried out by the NEMO Collaboration is described. The realization of a Phase-1 project, which is under way, will validate the proposed technologies for the realization of the km$^3$ detector on a Test Site at 2000 m depth. The realization of a new infrastructure on the candidate site (Phase-2 project) will provide the possibility to test detector components at 3500 m depth.

PACS: 95.55.Vj; 95.85.Ry

Keywords: Underwater Cherenkov Neutrino Telescopes

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 [1], the opening of the high-energy neutrino astronomy era can only be afforded with detectors of km$^3$ scale.

A first generation of “small” scale detectors has been realized (AMANDA [2] at the South Pole and NT-200 [3] in the Baikal lake) and have set limits on neutrino fluxes, while others are at different stage of realization (ANTARES [4] and NESTOR [5]). Following the success of AMANDA the realization of the IceCube km$^3$ detector [6] is now progressing at the South Pole. On the other hand, many issues, as the full sky coverage, strongly support the construction of a km$^3$-scale detector in Mediterranean Sea.

The activity of the NEMO collaboration has been 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$^3$ underwater telescope.

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 and a long term monitoring of the site has been carried out. Results of these measurements have been previously reported [7–9].

One of the efforts undertaken by the NEMO collaboration has also been the definition of a feasibility study of the km$^3$ 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 validation of the proposed technologies via an advanced R&D activity, the prototyping of the proposed technical solutions and their relative validation in deep sea environment is presently carried out with the two pilot projects NEMO Phase-1 and Phase-2.

2. General layout of the NEMO km$^3$ detector

The considerations leading to the definition of a proposed architecture for the km$^3$ detector have been described elsewhere [10]. We will here briefly recall the main characteristics of the detector.

The proposed NEMO architecture is a modular array of detection units, called “towers”, arranged in a $9 \times 9$ square lattice.

Performances of this detector, like effective area, angular resolution and sensitivity to point-like neutrino sources were evaluated by means of numerical simulations [10]. These simulations were carried out using the software [11] developed by the ANTARES collaboration and adapted to km$^3$ scale detectors [12]. In the simulation site dependent parameters such as depth, optical background, absorption and scattering length, have been set accordingly with the values measured in Capo Passero at a depth of about 3500 m.

3. The NEMO Phase-1 project

The NEMO Phase-1 project has allowed a first validation of the technological solutions proposed for the km$^3$ detector. The apparatus includes prototypes of the critical elements of km$^3$ detector: the junction box (JB) and the tower.

The apparatus has been installed at 2000 m depth at the Underwater Test Site of the Laboratori Nazionali del Sud in Catania, connected to the shore by means of a 28 km electro optical cable.

3.1. The junction box

The JB (Fig. 1) 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 silicone 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 oil bath.

3.2. The detector tower

The tower that hosts the optical modules and the instrumentation is a three dimensional flexible structure composed by a sequence of floors (that host the instrumentation) interlinked by cables and anchored on the seabed [13]. The structure is kept vertical by appropriate buoyancy on the top.

While the design of a complete tower for the km$^3$ foresees 16 floors, the prototype realized for the Phase-1 project is a “mini-tower” of four floors, each made with a 15m long structure hosting two optical modules (one down-looking and one horizontally looking) at each end (4 OM per storey). 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. 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.

A scheme of the prototype four floors tower is shown in Fig. 2. In addition to the 16 Optical Modules the instrumentation installed includes several sensors for calibration and environmental monitoring. In particular two hydrophones are mounted on the tower base and at the extremities of each floor. These, together with an acoustic beacon placed on the tower base and other beacons installed on the seabed, are used for precise determination of the tower position by means of time delay measurements of acoustic signals. The other environmental probes are: a Conductivity–Temperature–Depth (CTD) probe used for the monitoring of the water temperature and salinity, a light attenuation probe ($C^*$) and an Acoustic Doppler Current Profile (ADCP) that will provide continuous monitoring of the deep sea currents along the whole tower height.

The tower is designed such that it can be assembled in a compact configuration (see Fig. 3). This configuration is also maintained during the transport and the deployment, which is performed from a suitable surface vessel by means of a winch. Only after the correct positioning on the seabed and the connection to the undersea cable network, the tower is unfurled with a procedure that is actuated remotely and proceeds by using the pull provided by the buoy.

3.3. Tower cabling system

A number of considerations have lead to the design of the cabling system of the tower [14]. In particular fault
tolerance and ease of management have been taken into account.

At the base of the tower there is a Tower Base Module (TBM). The TBM is connected by means of a hybrid penetrator to the backbone cabling and by means of a hybrid connector to a jumper cable terminated with a wet mateable bulkhead that allows the interconnection of the tower to the JB by means of a ROV.

A lightweight electro-optical backbone cabling system distributes the power and the data transmission signals to and from the tower floors. The splitting of the cable is performed by means of breakouts positioned at each floor level. The breakouts are realized with pressure vessels each one containing two passive optical devices that perform the Add/Drop functions for the optical data transmission signals of the outgoing and incoming data flows.

Inside each floor structure two containers are installed: a Floor Power Module (FPM) and a Floor Control Module (FCM). This last one is the core of the system since it hosts all the floor electronics for data transmission. This module is realized with an analogous solution to that adopted for the JB: a metallic pressure resistant vessel placed inside an external plastic container filled with silicone oil and pressure compensated. The FPM is a silicone oil filled plastic container, since all the power supply subsystem that is hosted inside has been tested to operate under pressure [15]. The FCM is interfaced to the floor instrumentation by means of four electro-optical (for the OM) and three electrical (for the additional instrumentation) penetrators.

In this cabling system connectors are positioned only at the subsystems interfaces, to allow for testing of each single subsystem and for an ease of assembly, and at users interfaces. This allows to reduce their number thus reducing the cost of the system and increasing its reliability. Moreover, the use of penetrators instead of connectors minimizes the optical losses allowing for a higher budget for the data transmission system.

3.4. The optical module

The optical module is essentially composed by a photomultiplier (PMT) enclosed in a 17 in. pressure resistant sphere of thick glass. The used PMT is a 10 in. Hamamatsu R7081Sel with 10 stages.

In spite of its large photocathode area, the Hamamatsu PMT R7081Sel has a good time resolution of about 3 ns FWHM for single photoelectron pulses with a charge resolution of 35%.

Mechanical and optical contact between the PMT and the internal glass surface is ensured by an optical silicone gel. A mu-metal cage shields the PMT from the Earth’s magnetic field.

The base card circuit for the high voltage distribution (Isegi PHQ 7081SEL) requires only a low voltage supply (+5 V) and generates all necessary voltages for cathode, grid and dynodes with a power consumption of less than 150 mW.

A front-end electronics board, built with discrete components, has been designed, realized and tested [16]. This board is also placed inside the OM. Sampling at 200 MHz is accomplished by two 100 MHz staggered Flash ADCs, whose outputs are captured by an FPGA which classifies (according to a remotely programmable threshold) the signal as valid or not; stores it with an event time stamp in an internal 12 kbit FIFO; packs OM data and local slow control information; and codes everything into a bit stream ready to be transmitted on a differential pair at 20 Mbit/s rate. The main features of this solution are the moderate power consumption, the high resolution and the huge input dynamics obtained by a quasi-logarithmic analog compression circuit, and the fine time resolution. Through an incoming slow control channel, managed by a DSP, all the acquisition parameters can be changed, and there is the possibility to remotely reprogram the FPGA downloading new codes. Moreover, the board has embedded electronics, analog and digital, in order to control the Optical Module power supply to measure temperature, humidity and electrical parameters as well as to auto calibrate the non linear response of the logarithmic compressor.

3.5. Data transmission system

The design of the data transport system for NEMO Phase-1 has been based on technical choices that allow scalability to a much bigger apparatus [17,18]. Owing to synchronization purposes, a common timing must be known in the whole apparatus at the level of detection device to allow correlation in time of events. For this reason a synchronous and fixed latency protocol, which embeds data, synchronization and clock timing in the same serial bit stream, and allows an easy distribution of the clock signal to the whole apparatus, has been chosen. At the physical layer of communication the technology adopted relies on Dense Wavelength Division Multiplex
(DWDM) techniques, using totally passive components with the only exception of the line termination devices, i.e. electro-optical transceivers. The great advantages in terms of power consumption, reliability, and simplicity recommend this technique as a perfect candidate for the final km$^3$ detector.

The FCM on each floor collects data from the floor OMs and the auxiliary instrumentation, creates a data stream with a payload of 640 Mbps, and sends data toward the shore laboratory. From the opposite direction, the FCM receives slow control data, commands and auxiliary information, and the clock and synchronizations signals needed for apparatus timing. Bidirectional data transport is realized by means of the backbone optical fibre cabling system described in Section 3.3. In order to provide redundancy, data streams are doubled and re-directed onto two fibres using a “power splitter”. The one fibre of the two that is used to carry the meaningful information is chosen on the on-shore station.

The underwater structure has a mirrored on-shore counterpart, where all optical signals are reconverted into electrical signals. In the on-shore laboratory the Primary Reference Clock, which is used to give the same timing to all the towers of the apparatus, is also located. Assuming that the two fibres per tower maintain their integrity, the designed system provides other experiments with a further bidirectional channel.

### 3.6. Electrical power system

For the Phase-1 project a three phase AC system has been chosen since it presents some advantages in terms of voltage drops and reliability. This system is used for the energy distribution up to the level of the local electronics module in each storey where a conversion to DC is made [15].

A control system has been realized to acquire all the relevant data such as currents, voltages and environmental parameters (temperature, humidity, etc…) inside the containers.

The system has been designed to have a large part of its components working under pressure inside an oil bath. For this aim extensive tests on electric and electronics components have been performed [15].

### 3.7. Calibration and control systems

The timing calibration requires an embedded system in order to track the possible drifts of the time offsets during the operations of the apparatus underwater [19]. The task of this embedded system is essentially to measure the offsets with which the local time counters inside the optical modules are reset on reception of the reset commands broadcasted from the shore, i.e. the time delays for such commands to reach the individual optical modules. All time measurements are in fact referred to the readout of such counters. The operation will be performed with a completely redundant system [18]: (1) a two-step procedure for measuring the offsets in the time measurements of the optical sensors and (2) an all-optical procedure for measuring the differences in the time offsets of the different optical modules.

In the first system the needed measurements are performed in two separate steps: using an “echo” timing calibration and using an “optical” timing calibration.

The former will allow us to measure the time delay for the signal propagation from the shore to the FCM of each floor; the latter, which is based on a network of optical fibres which distributes calibration signals from fast pulsers to the optical modules, will allow to determine the time offsets between the FCM and each optical module connected to it. The second system is an extension of the optical timing calibration system, which allows to simultaneously calibrate the optical modules of different floors of the tower.

An essential requirement for the muon tracking is the knowledge of each sensor position. While the position and orientation of the tower base is fixed and known from its installation, the rest of the structure can bend under the influence of the sea currents. A precise determination of the position of each tower floor is achieved by means of triangulation measurements performed by measuring time delays of acoustic signals between acoustic beacons placed on the sea floor and a couple of hydrophones installed on each tower floor. In addition to this the inclination and orientation of each tower floor is measured by a tiltmeter and a compass placed inside the FCM.

The acoustic Long Base Line (LBL) is realized with four standalone battery-powered acoustic beacons and one additional beacon located on the tower base. The accuracy on the measure of the flight time is of the order of 10$^{-4}$s which yields an accuracy on the estimation of each hydrophone position of 15 cm.

To determine the position of the hydrophones the LBL must be synchronised to the master clock of the apparatus. This synchronisation takes place acoustically using a monitoring station placed in correspondence to the tower base.

All the Slow Control data (including data from all environmental sensors and the acoustic positioning system) are managed from shore by means of a dedicated Slow Control Management System [20].

### 4. Installation and operation of NEMO Phase-1

#### 4.1. Deployment and installation

The NEMO Phase-1 system was successfully installed in December 2006 in a sea operation conducted with the cable layer vessel TELIRI.

The JB and the tower were deployed from the surface by means of a winch (Fig. 4) and positioned at 2100 m depth with an accuracy of a few meters with respect to the target positions.
Prior to the connection of the system, the four acoustic beacons providing the LBL for the acoustic positioning system were deployed around the apparatus at an approximate distance of 500 m. Their relative position was determined with the desired accuracy of 10 cm with the help of the ROV equipped with a suitable calibration tool.

The JB was connected to the main cable termination frame and the tower to the JB with electro-optical links equipped with wet mateable hybrid connectors. Connection operations were performed with an underwater Remotely Operated Vehicle (ROV).

The operation was completed with the successful unfurling of the tower that assumed the correct configuration.

4.2. First data and performance

After several months of operation no water leakage was detected in any component of the tower.

The data taking and analysis started soon after the deployment and the correct functioning of the system was verified.

The data transmission and acquisition system has been successfully tested, meeting its target performances [21]. As an example the time development of the average rate values of an OM is shown in Fig. 5: the shown data sample has been acquired during 18 h starting from the 10th of January 2007 at 21 h. The thick plateau at about 73 kHz is the hit rate baseline, due to the contribution of both $^{40}$K and diffused bioluminescence; the high peaks emerging from the baseline and reaching values up to 5 MHz are caused by localized bioluminescence activity.

Also the acoustic positioning system was satisfactorily tested, the three dimensional measurements of the positions of the various hydrophones were taken simultaneously and then the 3D distance of the two hydrophones was measured.

Fig. 6 shows the results of this operation, carried out on the second floor of the tower. The mean length of the distance of the hydrophones was measured as 14.22 m and more than 80% of the data falls within 10 cm of the mean.

The time calibration system was able to reconstruct the calibration signal with the accuracy requested ($\sigma \approx 1.5$ ns), as shown in Fig. 7.

A preliminary track reconstruction of the downgoing atmospheric muons was also performed, an example is shown in Fig. 8.

Nevertheless some problems occurred after some months of functioning. The buoyancy of the tower decreased with the time, producing a lowering of the tower position.

The problem originated in the construction process of the buoy that will be improved for the realization of the new tower for the Capo Passero installation (Phase-2).

Another problem was related to a malfunction inside the JB that requires the recovery for a full diagnosis.

The main results point out a malfunctioning of the optical penetrator. Consequently this component will be modified in the design and construction for the new tower of Phase-2.

5. The NEMO Phase-2 project

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.

Fig. 6. Accuracy of the acoustic positioning system.

Fig. 7. View of the control panel of the time calibration system. The acquisition times of the hits triggered by flashes of the calibration pulsers are compared to the expected values, in order to calculate the time offsets of the individual optical modules. The left panel shows a low-resolution histogram of the acquisition times of calibration hits while a high-resolution zoom of the peak area is shown in the right panel.

Fig. 8. Reconstruction of a downgoing atmospheric muon track.
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 end of 2008, 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.

5.1. Phase-2 main electro-optical cable

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 [22]. 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 second half of 2008.

6. Conclusions and outlook

The activities of the NEMO collaboration have recently progressed with the achievement of a major milestone: 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.

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. The realization of the deep-sea infrastructure has begun with the deployment of the long electro-optical cable while a shore station is under construction near the mole of Porto Palo harbor. After a careful revision of its design, following the experience gained with the Phase-1 project, the construction of a fully equipped 16 storeys tower is under way. The tower will be installed and connected by the end of 2008.

A further R&D program is also underway within the KM3NeT consortium [23] in which all the European institutes currently involved in the Mediterranean neutrino astronomy projects are participating. The project, partly supported by the European Union, has started in February 2006 a three year Design Study, which aims at producing a Technical Design Report for the realization of an underwater Cherenkov km$^3$-scale neutrino telescope. This will be followed by a Preparatory Phase project, that will start early 2008, that aims at defining all the aspects needed to bring the km$^3$ detector at the construction phase.

References

[21] F. Simeone, for the NEMO Collaboration, in these proceedings.
[23] U. Katz, Nucl. Instr. and Meth. A 567 (2006) 456; E. de Wolf, in these proceedings; the KM3NeT website is at; ⟨http://www.km3net.org⟩.