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Long term monitoring of the Capo Passero deep-sea site with the NEMO tower prototype ⋆

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Abstract In the framework of the NEMO (NEutrino Mediterranean Observatory) project, the NEMO Phase-2 tower is the first detector which has been operating for more than year long at the record depth of 3500 m below the see surface. The 380 m long tower has been successfully installed in March 2013 80 km off-shore Capo Passero (Italy). This was the first prototype installed on the site where the italian node of the KM3NeT neutrino telescope, whose inner core will be realized with eight towers, will be built. The installation and oleration of the NEMO Phase-2 tower has proven the functionality of the infrastructure and the operability at 3500 m depth as well as providing a more than a year long monitoring of the deep water characteristics of the site. In this paper the infrastructure and the the tower structure and instrumentation are described. The results of long term optical background measurements are presented. In particular, the analyzed rates show stable and low baseline values, compatible with the contribution of ^{40}K light emission, with a small percentage of light bursts due to bioluminescence. All these features are a confirmation of the stability and good optical properties of the site.

1 Introduction

High energy neutrinos are expected to be a new precious messenger from astrophysical distant objects in which hadronic interaction take places. In this framework several projects were developed (see refs. [1, 2]). The recent discovery of a cosmic neutrino flux from IceCube [3] initiates the era of neutrino astronomy confirming that km^3 is the needed scale for a high energy ($E \geq$ TeV) neutrino telescope. However most of the questions raised about the origin of the observed neutrino cosmic flux remain unsolved. Many hypotheses have been proposed including galactic and extragalactic sources, Dark Matter etc. As a consequence of this discovery the physics case for the construction of a km^3-scale neutrino telescope in the Northern Hemisphere is strongly enforced. Indeed, a telescope in the Mediterranean Sea, due to the Earth rotation, has a field of view of about 87% of the Galactic Plane, therefore it not only observes the neutrino sky complementary to the IceCube one, but has also a large region of overlap with the IceCube field of view. Moreover, the far better angular resolution achievable w.r.t. to IceCube, due to the large scattering length ($\geq$ 200 m CHECK!) in deep sea water, strongly enhances the potential discovery and eventually a good pointing accuracy increases the possibility of source identification.

Starting from 1998, the NEMO (NEutrino Mediterranean Observatory) collaboration carried out research activities aimed at developing and validating key technologies for a cubic-kilometer scale underwater neutrino telescope [4–7] as well as searching and characterizing a deep-sea site suitable for the installation of the detector. The first pilot project NEMO Phase-1 took place in 2007, when a prototype mini-tower was deployed in the Test Site, a 2000 m deep submarine location about 20 km offshore Catania (Italy). The details of NEMO Phase-1 and the obtained results can be find in [8].

A deep-sea site with proper features in terms of depth and water optical properties has been identified at a depth of 3500 m, about 80 km offshore from Portopalo di Capo Passero, in the south-east extremity of the Sicilian coast.

In 2008, a 100 km electro-optical cable was deployed from the onshore infrastructure located in Portopalo di Capo Passero (Italy) to the offshore location. In the following years, the validation of the proposed technologies went on through an intense R&D activity, up to the second stage of proto-

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typing, the NEMO Phase-2 tower. Since its deployment, occurred in March 2013 in the Capo Passero site, the Phase-2 tower has been continuously taking data until August 2014 when it was disconnected to allow for an upgrade of the underwater infrastructure in preparation of the installation of the first group of detection structures that will form the italian node of the KM3NeT detector.

In this paper we will describe the Capo Passero site and infrastructure, the tower detection system as well as the performed optical background and environmental measurements.

2 The Capo Passero site and infrastructure

A deep site with proper features in terms of depth and water optical properties was identified at a depth of 3500 m, about 80 km offshore from Portopalo di Capo Passero (province of Siracusa, Italy), in the south-east extremity of the Sicilian coast (Fig. 1). A series of campaigns to study and to monitor the most important environmental parameters was then carried out. Oceanographical properties of the site, like deep-sea water optical properties (absorption and diffusion), water environmental properties (temperature, salinity), biological activity, optical background, water currents, sedimentation and seabed nature were studied [9, 10]. This activity has confirmed that the Capo Passero site has optimal characteristics and will host the italian node of the KM3NeT research infrastructure. *Questa affermazione va supportata da una discussione piú articolata*

On this site, an infrastructure has been realized. It consists of a shore station, a 100 km long electro-optical cable and a deep-sea installation comprising a novel design 10 kW DC voltage converter. The onshore infrastructure, located in Portopalo di Capo Passero, hosts the power feeding system, which directly feeds the main 100 km long main electro-optical cable (MEOC) [11], as well as the control centre and data acquisition system.

The MEOC is a standard submarine communication cable manufactured by Alcatel[1] containing 20 (INSERIRE IL CODICE FIBRE) optical fibres. These fibres have a maximum attenuation of 0.23 dB/km. The cable has a single conductor for power transmission. Current return is provided via seawater, which offers an extremely small resistance thus reducing the power losses [12]. The system incorporates sea electrodes both at the shore and at the deep-sea ends.

At the deep-sea end the MEOC is terminated by a Cable Termination Frame (CTF) hosting a Cable Termination assembly, allowing to split and reroute the fibres towards a connection panel, and a DC Medium Voltage Converter (MVC), allowing to step down the 10 kV provided by the onshore Power Feeding System (PFE) to 375 V [13]. *Va ag-*

[1]Model OALC - 4 17 mm Type 30.

Fig. 1 Map of the western Ionian region showing the location of the Capo Passero deep-sea site and the electro-optical cable route.

Fig. 2 Scheme and photo of the Cable Termination Frame

giunto uno schema della terminazione aggiustando in accordo la descrizione

3 The NEMO Phase-2 tower

The tower is a semi-rigid vertical structure composed of eight horizontal elements (named *floors*) interlinked by a system of tensioning ropes [14] (see Figure 3). The structure is anchored to the seabed by a dead weight and kept taut by an appropriate buoyancy at the top. Each floor is a 8 m long marine grade aluminum structure that is connected to the next one with four ropes such that each floor is forced to a position perpendicular to its vertical neighbours, as shown in Fig. 3. The floors are vertically spaced by 40 m, with the lowermost one one positioned 100 m above the sea bottom. Each floor holds four optical modules, two at each end, one looking vertically downwards and the other horizontally outwards. The structure is designed to be assembled and deployed in a compact configuration (see Figure 4) and

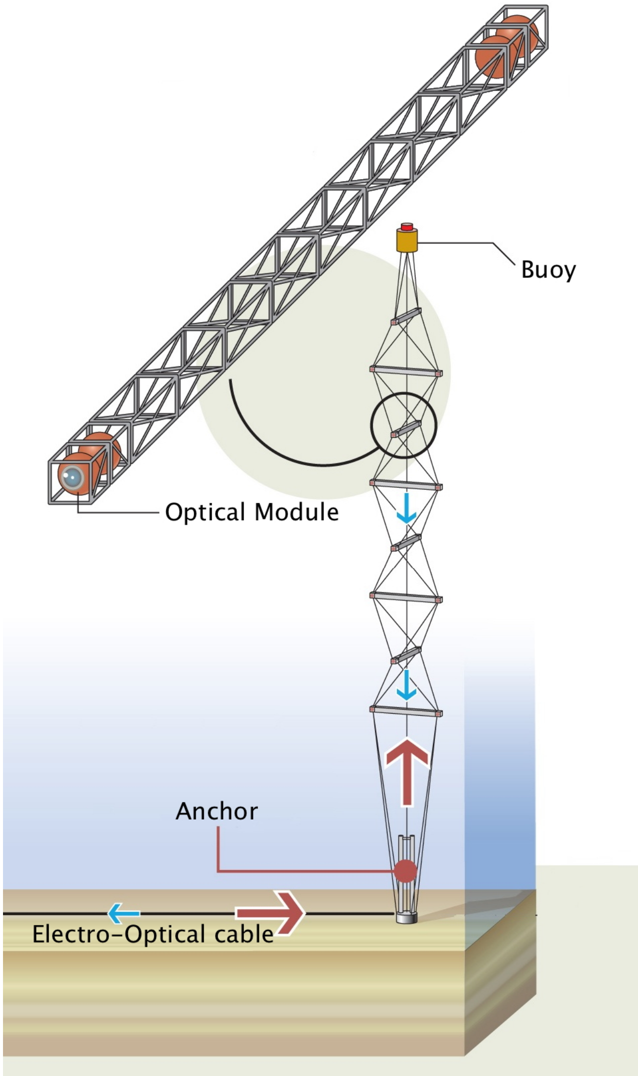

Fig. 3 Sketch of the NEMO Phase-II tower. The structure is formed by a sequence of eight stories, each one supporting four optical modules. The whole structure is anchored on the seabed and kept taut by a buoy located at the top. Vertical distances are not to scale.

Fig. 4 The tower in compact configuration during the integration phase.

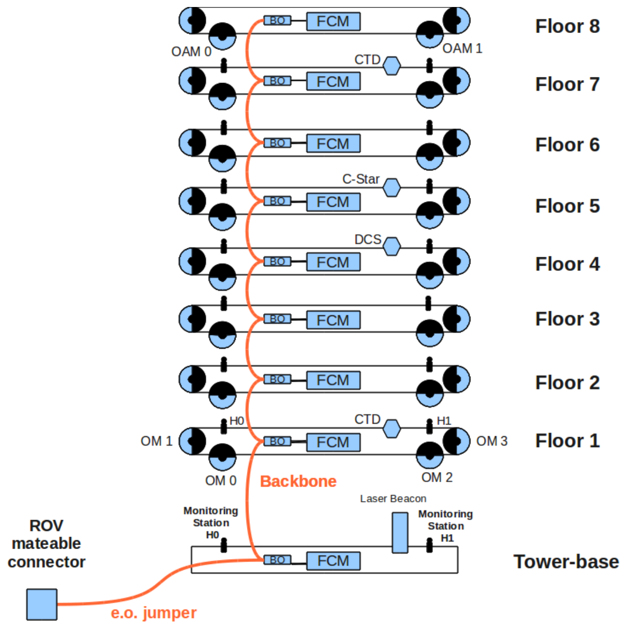

Fig. 5 Schematics of the NEMO Phase-2, including the backbone cabling (orange), the Floor Control Modules (FCM) and the electro-optical breakouts (BO). Connection to the Junction Box is provided through a ROV-mateable hybrid connector, installed in the tower base.

to be unfurled on the sea bottom under the pull provided by the buoy.

A schematics of the tower is show in Fig. 5. In addition to the 32 Optical Modules the instrumentation installed includes several sensors for calibration and environmental monitoring. In particular two hydrophones are mounted close to the extremities of each floor and two other on the tower base. Being the deep seawater a dynamical medium, monitoring of its oceanographic and optical properties during the detector operation is also important since they can have an impact on the detector performances. For this reason several environmental probes are installed on the NEMO Phase-2 tower: two Conductivity–Temperature–Depth (CTD) probes [2], installed on the 1^{st} and 7^{th} floor at a depth of 3349 m and 3109 m respectively; a light transmissometre used for the measurement of blue light attenuation in seawater; a Doppler Current Sensor (DCS) used to monitor deep sea currents installed on the 5^{th} at a depth of 3189 m .

Power distribution and data transmission along the tower is fulfilled by means of a "backbone" electro-optical cable. This is a lightweight umbilical subsea cable [3], carrying 10 electrical conductors and 12 optical fibres.

[2] Sea Bird Electronics, 37-SM Micro-CAT.
[3] Nexans

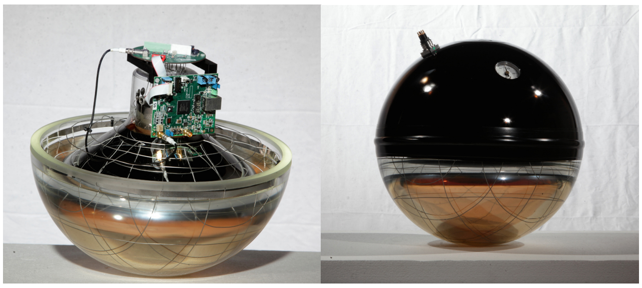

Fig. 6 Left: Semi-sphere of optical module holding the photomultiplier and the Front-End Module board. Right: Optical module fully integrated with connector and pressure meter.

3.1 The Optical Modules

The Optical Modules (OM) are the basic elements of the NEMO Phase-2 device [15, 16]. Each OM consists of a 13-inch pressure resistant (up to 700 bar) borosilicate glass sphere [4], housing a 10-inch Hamamatsu PMT R7081-SEL together with its read-out electronics and and calibration system (see Figure 6). Mechanical and optical contact between the PMT and the internal glass surface is ensured by an optical silicone gel. A μ-metal cage shields the PMT from the Earth's magnetic field. A detailed description of the NEMO Phase-2 optical modules is given in [15].

PMT signal digitization is provided by a Front-End Module (FEM) board also housed inside the OM. The board samples the analog PMT signal using two 8-bit Fast Analog to Digital Converters (Fast-ADCs) running at 100 MHz and staggered by 5 ns. This technique gives the desired sampling rate yet allowing a power dissipation lower than a single 200 MHz ADC. To match the [$0 \div 5$ V DC] input dynamic range of the PMT base to the 1024 mV input voltage range of the ADCs, the signal level is shifted and compressed by a non-linear circuit, which applies a quasi-logarithmic signal compression.

3.2 Electronics and Cabling

A simplified scheme of the electronics and cabling of the tower is shown in Fig. 7. At the level of each floor the backbone is split by means of breakout boxes (BO) Each breakout is a High Density Polyethylene vessel filled with silicone oil and pressure compensated. The BO equipped with two hybrid penetrators, which are used to split the backbone, and two connectors (one electrical and one optical) to connect the backbone to the floor cabling system.

On each floor the data acquisition, control and power distributions systems are housed in a pressure resistant vessel, the Floor Module POD (Protective Oceanic Device),

[4] glass sphere

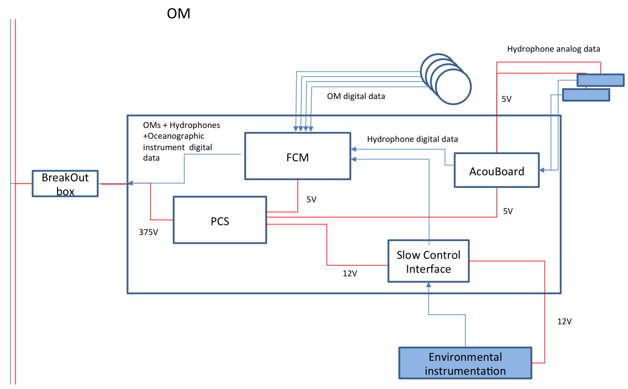

Fig. 7 Schematics of the floor system.

which is fitted in the middle of the floor mechanical structure.

The 375 V supplied by the MVC is monitored at the level of the tower base and distributed to the eight floors. Inside the floor POD a Power Contol System (PCS) board provides conversion of the DC supply from 375 V to the low voltages needed by the electronics as well as monitoring and control of all the main electrical parameters of the floor.

A Slow Control Interface (SCI) board provides interface, via RS-232 serial standard, to the oceanographic instruments installed on the floor. In addition, each SCI has on board two analogue sensors to monitor humidity and temperature inside the floor POD.

3.3 Data Transmission System

The link to the shore-station uses an optical fibre as physical layer and implements a high speed serial link using a proprietary data format [17]. All data are encoded into a serial 800 Mb/s stream by a serializer, converted into optical signal by an electro-optical transceiver and transmitted to the shore station. In the communication protocol the data stream is divided in 125 μs long frames of 10000 bytes each.

A transmission system through optical links based on Dense Wavelength Division Multiplexing (DWDM) technology was chosen. It is implemented by means of *add-and-drop* passive devices which mux/demux many optical channels at different wavelengths into/from the same fibre. A specific wavelength is associated to each floor of the detector. The optical wavelengths are chosen according to the ITU standard grid with 100 GHz frequency spacing in the C-Band thus allowing up to 45 channels per fibre. The DWDM network allows, indeed, a *point-to-point* communication between the shore-station equipment and the deep-sea apparatus. In such a network each communication link shares the same physical medium without being affected by the other links. Each FCM contains an add-and-drop filter that allows to add or subtract the specific optical wavelength allocated to the floor. Data from all floors are thus transmitted through the backbone in the same fibre.

Detector data are received onshore by dedicated electronics, based on a Virtex 5 development board, that collects the information produced by the underwater electronics and make them available, through a Gigabit Ethernet connection, to the DAQ and storage systems.

3.4 Data Acquisition System

To minimize the number of possible failure points in the abyssal site, no hardware triggers are implemented underwater: all the digitized signals are sent to shore. The total available bandwidth for the optical data from the tower is 2 Gbps. Each data-stream originated by one eFCM is addressed on shore to a twin board (EFCM), which transfers the data to the onshore Trigger and Data Acquisition System (TriDAS) [19].

Each detected single photon pulse is sampled by the FEM and arranged by the FCM in a hit record with a mean size of 28 bytes. The tower averaged optical throughput results to be about 250 Mbps. The total amount of data from offshore includes also an additional 10 per cent of acoustic data produced by the positioning system and a negligible contribution of slow control data. The NEMO electronics was designed to deal with an optical signal up to 150 kHz continuous single rate on each PMT without dead time.

From the EFCMs, the PMT optical data-stream is routed through a 1 GbE network to the first layer of the TriDAS, composed of two Hit Managers (HMs). Each HM gathers data form half a tower and coherently time-slices the continuous stream of data into time intervals 200 ms wide. All the data corresponding to a given interval of time are sent by the HMs to a single TriggerCPU process (TCPU). Subsequent timeslices are addressed to the others TCPU processes, whose number can be increased according to the CPU requirements of the implemented trigger algorithms. The TCPU processes implement the trigger algorithms for background rejection. A reduced selected stream is then addressed, through a 1 GbE switch, from all the TCPUs to the Event Manager (EM) server which is deputed to write the post-trigger files on the local temporary storage device.

The selected data are compound into binary formatted post-trigger files which are automatically copied from the Portopalo center to the persistency storage facility at the LNS by means of a dedicated 1 GbE point to point connection.

3.5 Positioning and calibration

3.5.1 Acoustic positioning System

Since the tower structure is not rigid, floors are subject to the effects of deep-sea currents than can distort the line shape of the tower away from the vertical, making the floors rotate and tilt. For a proper reconstruction of the muon tracks, which is based on space-time correlation of Cherenkov photons hitting the OMs, the knowledge of the position of each OM with a precision of the order of 10 cm is needed. This can be obtained by using a system based on acoustic triangulation as demonstrated by previous experience gained with the NEMO Phase-1 prototype.

The NEMO Phase-2 prototype hosts aboard the Submarine Multidisciplinary Observatory (SMO) acoustic array, funded by the Italian Ministry of Research, University and Education (MIUR)-FIRB-2008 . The aims of SMO are to perform the acoustic positioning of the NEMO Phase-2 detector and to provide the monitoring the underwater acoustic environment of the area [21]. The SMO acoustic array is composed of 10 large broadband hydrophones (10 Hz - 70 kHz), model SMID TR-401, placed along the detector at different depths, from 3150 m to 3350 m of depth [22]. In addition to the previous sensors, a couple of free flooded rings (FFR) hydrophones manufactured by Sensor Technology Ltd, model SX-30 and provided by UPV in collaboration with CPPM-CNRS are installed at a depth of 3110 m and at a depth of 3350 m, the NEMO-Phase II detector hosts two special Optical-Acoustic Modules (OAMs), equipped with a custom piezoelectric sensor developed by Erlangen Centre for Astroparticle Physics (ECAP). Data from all acoustic receivers are sampled off-shore at a sampling frequency of 192 kHz and a resolution of 24 bit. Acquired acoustic data are continuously sent to shore and labelled with the absolute time of acquisition off-shore thanks to a data acquisition system synchronous and phased with the GPS time station, installed on the shore laboratory [22]. The NEMO Phase-2 detector includes also a minimal LBL of 3 autonomous acoustic beacons.

An independent real time monitoring the floors orientation is provided by an Attitude Heading Reference System (AHRS) board placed inside each FCM vessel. It consists of MEMS gyroscopes, accelerometers and magnetometers on all three axes. The floor yaw, pitch and roll are calculated by means of a 9^{th} order extended Kalman filter.

3.5.2 Time calibration System

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4 Installation and operation

The NEMO Phase-2 tower was deployed on March 23 2013 during a sea campaign operated by the Multi Service Vessel 'Nautical Tide' [5]. The tower deployment operations took approximately 6 hours. The tower was first lowered to the seabed, using the ship hydraulic frame, and then connected to the CTF by means of a surface controlled Remotely Operated Vehicle (ROV). After the connection the tower was unfurled reaching its operating configuration. Data acquisition started immediately after.

During the same operation one autonomous acoustic beacon was also deployed at about 400 m North of the tower. A second one was installed on July 20 2013 at about 400 m East of the tower. Together with the one installed on the tower base they form the acoustic Long Baseline (LBL) system. These beacons were not synchronized to the GPS clock distributed from shore. Their time of emission had to be resynchronised with respect to the detector clock by means of the monitoring hydrophone mounted on the tower base in a fixed and known position. After the deployment this hydrophone was found not to work properly, thus preventing the possibility of calibrating the LBL system. Consequently it was not possible to determine the position of each single hydrophone of the tower. However, information on the vertical position of the tower could be deduced by the data provided by the CTD probes which were found to be at the expected depths of 3358 m (1^{st} floor) and 3118 m (7^{th} floor). This information was checked by measuring the time delays of acoustic signals, emitted by the beacon installed on the tower base, between the lowermost (1^{st}) floor and the other floors and found to be consistent with the CTD data.

However acoustic data permits, also in this reduced configuration, to recover the orientation (heading) and pitch and roll of each floor with a precision better than 1 degree, in agreement with the compass data.

Combining the acoustic data with depth information recovered by the two CTDs and assuming a fixed distance between floors of 40 m and a 5 m uncertainty on the position of the LBL beacons determined by the ship GPS system at the time of deployment, it was possible to calculate via a global fit algorithm, the position of each hydrophone with an error estimated at about 1 m.

*In some specific runs a new test device, i.e. a beacon located at the tower base whose emission is synchronous with the master clock [**?**], was used. In this case it was possible to determine the position of each hydrophone with about 30 cm accuracy and reduce the effect of systematic errors.*

As an example, a Floor heading reconstruction by using the hydrophones system is shown in Figure 8 for a couple of days measurements. This is in good agreement with the AHRS heading reconstruction (15 minutes averages) normalized to the hydrophones data.

[5] MTS/FUGRO Chance Company

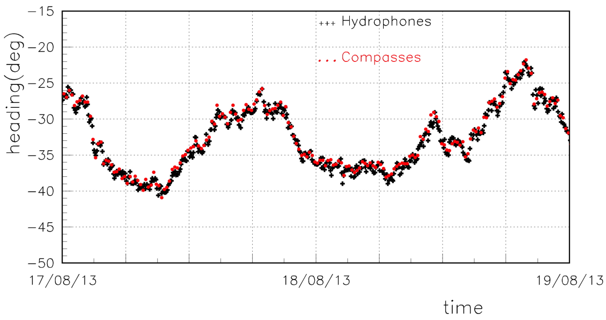

Fig. 8 Orientation of Floor 6 determined using the hydrophone data (black crosses) compared to the heading information determined by the Attitude Heading Reference System (AHRS) on board the Floor Control Module.

In spite of the lack of a precise positioning of each single OM it was however possible to reconstruct downgoing muon tracks and determine the Depth Intensity Relation of muons in water as reported in [20]

High Voltage on each PMT was adjusted to obtain the same gain factor of 5×10^7. This converts each single photon electron (s.p.e.) into an amplified cascade with a mean integrated charge of about 8 pC. During a commissioning phase that lasted up to xx May 2013 several adjustments of the PMT gains were made. As a consequence data rates reported in the following have to be considered stable only after this date.

5 Long term monitoring of the optical background

During its seventeen months of operation the NEMO Phase-2 tower allowed for a continuos long term monitoring of some site characteristics. In particular, the optical background rate, which is due to the presence of Cherenkov light produced in the decay of ^{40}K as well as light emitted by bioluminescent organisms, was studied.

Figure 9 shows the distribution of the time difference between successive hits, Δt, on the post-trigger data of a typical OM, showing the expected exponential form with a slope of $\tau = 1.8 \times 10^{-4}$ s corresponding to a purely random background singles rate of about 55 kHz.

The singles rates have been evaluated by a complete GEANT4 simulation, including the PMT dark count and the contribution to the background from the presence of radioactive materials in the glass sphere, both measured in the laboratory, as well as the the water absorption length of the Capo Passero site. The results of this simulation gave a value of 54 ± 3 kHz in perfect agreement with the in situ observed rate.

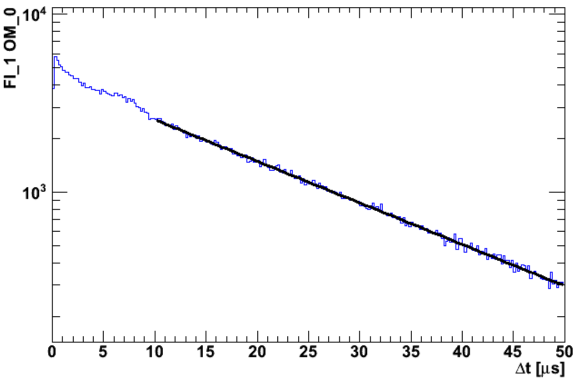

Fig. 9 Histogram of the time difference between two consecutive hits. The exponential fit above $\Delta t = 10\mu s$ (black like) gives a characteristic time $\tau = 1.8 \times 10^{-4}$. The bump at $\Delta t \approx 7\mu s$ is due to the presence of PMT afterpulses. I NUMERI SONO DA VERIFICARE!

The rates determined as in Fig. 9 on the post-trigger data suffer by the dead time introduced by the data acquisition system that limits the maximum data rate transferable to about 100 kHz. However, the FEM board on each OM provides an independent monitoring of the average count rate by counting once per second the number of hits with amplitude exceeding a threshold of 0.25 single photo-electron (s.p.e.) in a 10 ms time window. This estimate does not suffer of dead time limitations allowing to monitor the signal rate up to about 6.5 MHz.

Figure 10 shows the distribution of the singles rates in one OM for two one-hour time slots taken in different periods with different background characteristics. In the the top panels (A and B) the rate is shown as a function of time. In the bottom panels (C and D) the corresponding histograms of the rate distributions are shown. In general, the instantaneous rate exhibits a flat baseline at around 55 kHz with some sporadic bursts. The baseline corresponds the contribution of the ^{40}K discussed above while light bursts can be attributed to the presence of bioluminescent organisms. The presence of these bursts can vary in time, as shown by the two examples in Fig. 10. To monitor these variations, as well as possible variations in the baseline rate, the rates have been studied by determining for 15 m time frames the baseline and the fraction of time for which the rate exceeds 100 kHz.

In Figure 11, the baseline rate for eight down looking OMs located at different depths is shown for the whole operation period of the tower. Red dots evidence the commissioning period of the tower. The observed baseline rates are constant and in agreement with the previous measurements performed in the same site. The average value for the whole measurement period and for all floors is compatible with the estimate of the ^{40}K contribution.

For the same set of eight down looking OMs the probability density function of having a rate exceeding 100 kHz

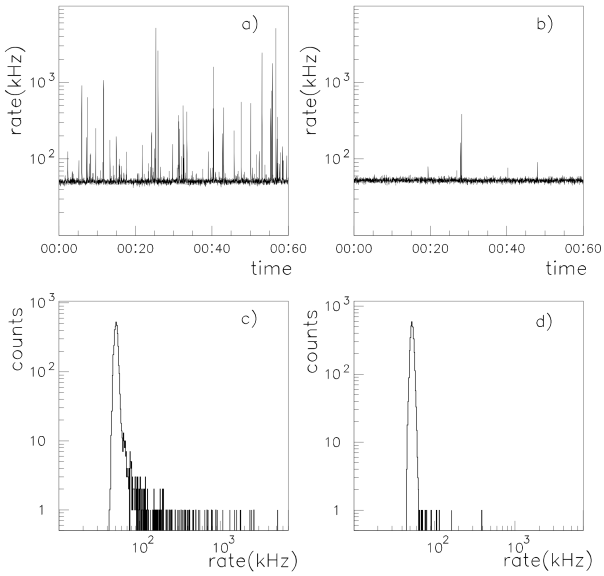

Fig. 10 Singles rated for one nor time slots measured on July 7 2013 (panel a) and on September 11 2013 (panel b). Panels c) and d) show the corresponding rate distributions.

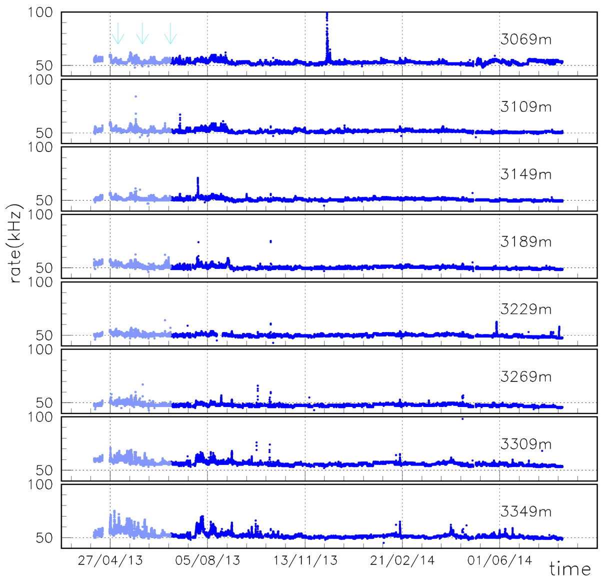

Fig. 11 Bseline rate measured in 15 m time slots for the whole operation period of the tower and for different depths. All the PMT selected are down-looking. Light blue dots evidence the commissioning period of the detector. The arrow on top indicate the dates when PMT high voltage adjustments were performed.

is reported in Figure 12. This effect can be seen also in Figure 13 (upper panel) where the probability density function of the rate has been calculated after the last HV adjustements for the period going from July 2013 till August 2014. In particular, the low contribution of bioluminescence bursts is shown for an optical module located on the lowermost floor of the tower. For the examined PMT, the rate distribution is

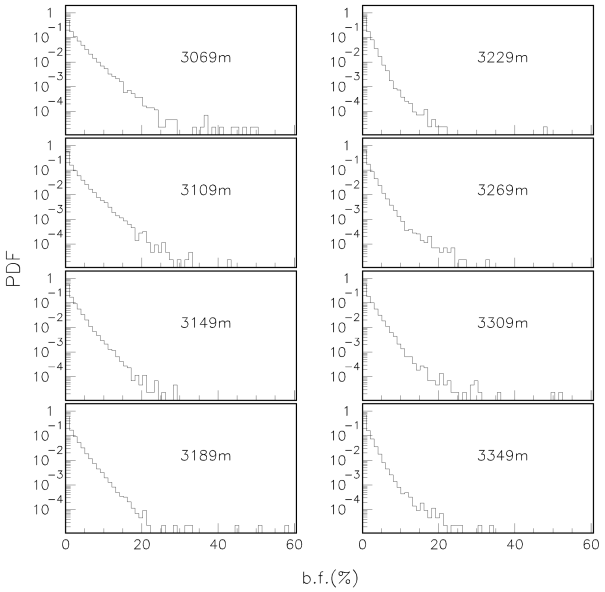

Fig. 12 Probability density function of observing a rate exceeding 100 kHz in eight OMs placed at different depths.

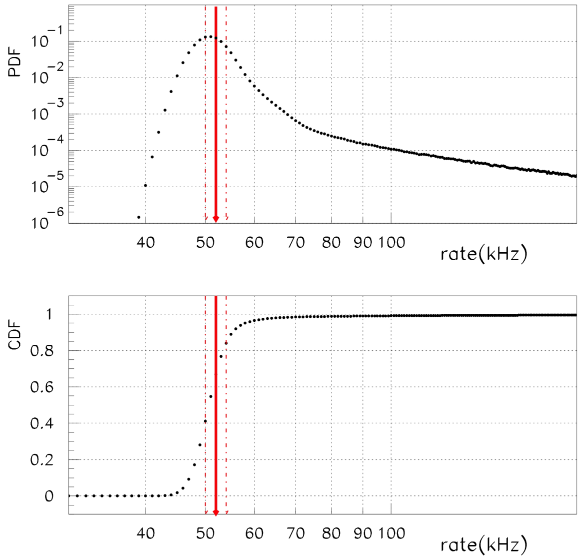

Fig. 13 In black, rate Probability Density Function (PDF) and Cumulative Density Function (CDF) for data starting from June 2013 to August 2014. The solid red line corresponds to GEANT4 simulation results for background. Dashed red lines give the error in such simulation.

peaked around 50 kHz and becomes negligible above 100 kHz. The other optical modules show very similar behaviors with peaks located in the range 45-55 kHz. The cumulative density function of the rate has also been calculated and it reaches the value of 1 in the range 100-200kHz. This lead to the important conclusion that the probability to have the TRIDAS in dead time is very small all along the full year observation. There is no period in which the OM's need to be switched off for high bioluminescence activity.

For sake of completeness the time behaviour of the small bioluminescence activity is shown in Figure 14 for a 15 days time series. There is evidence of periodic behaviour due to the presence of inertial currents which at the tower latitudes have a period of 20.21 h. Further analysis of bioluminescence correlation with sea currents is in progress.

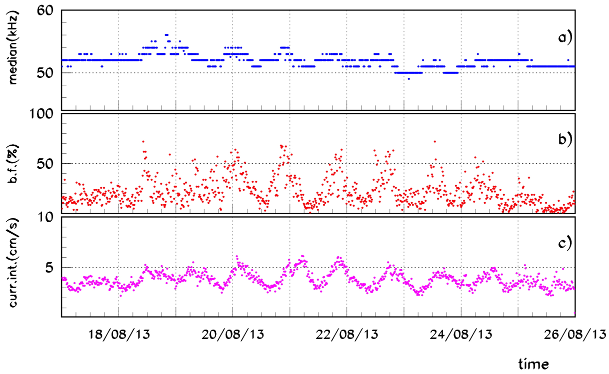

Fig. 14 a) baseline rates rates over a 15 minutes period; b) fraction of time in the 15 minute window with rate exceeding 100 kHz; c) water current intensity.

6 Conclusions and perspectives

Deployed in March 2013 in the abyssal site of Capo Passero at the depth of 3500 m, the NEMO Phase 2 tower has been continuously taking data, validating the technical solutions proposed for an underwater Cherenkov detector. The first data analyses have confirmed the optimal environmental characteristics of the site which, starting from 2015, will host the next generation of underwater neutrino telescopes.

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