Recent results from NESTOR

L K Resvanis representing the NESTOR Collaboration

NESTOR Institute, National Observatory of Athens and Physics Dept., University of Athens

E-mail: Leonidas.Resvanis@cern.ch

Abstract. A module of the NESTOR underwater neutrino telescope was deployed at a depth of 3800 m in order to test the overall detector performance and particularly that of the data acquisition systems. A prolonged period of running under stable operating conditions made it possible to measure the cosmic ray muon flux, \( I_0 \cdot \cos^a (\theta) \).

1. Introduction

When high-energy neutrinos interact with matter, some of the time they produce relativistic muons that follow closely the direction of the incident neutrinos. When such interactions occur in the sea water or bedrock close to the detector, these muons can be observed by the Cherenkov light that they emit using arrays of sensitive optical detectors: from the arrival time and intensity of the light pulses detected, the direction of the muons, and hence those of the incident neutrinos, can be reconstructed.

The potential of such detectors for astronomy and cosmology has long been recognised. After the pioneering work by DUMAND near Hawaii, detectors are currently operating at Lake Baikal (Siberia) and in ice at the South Pole (AMANDA). Construction of a large array (ICECUBE) is starting at the South Pole and the need for a complementary detector (~ 1 km) in the northern hemisphere has led to a number of projects in the Mediterranean.

2. Main features of the NESTOR Detector, its site and infrastructure

A number of reports and papers have described in detail the elements of the NESTOR detector and the techniques used for its deployment and recovery. The main features are only briefly reviewed in this section. The prerequisites for the site are deep (several km), clear water, low underwater currents, very low bioluminescent activity, minimal sedimentation and biofouling rates as well as close proximity to support infrastructure on shore. The NESTOR site in the Ionian Sea off the southwestern tip of the Peloponnesse fulfils all these requirements. Extensive surveys in 1989, 1991 & 1992 located a large flat plateau of 8 x 9 km\(^2\) in area at a mean depth of 4000 metres. Situated on the side of the Hellenic Trench that lies between the west coast of the Peloponnesse and the submarine mountain chain of the East Mediterranean Ridge, the site is well protected from major deep-water perturbations. The deepest water in the Mediterranean at 5200 metres is a few miles away from the NESTOR site. Very deep water is essential in reducing the principal background from muons produced by cosmic rays.
interacting in the Earth’s atmosphere. Also biological activity diminishes with depth. The location is 7.5 nautical miles from the island of Sapienza, where there are two small harbours, and 11 miles from the port of Methoni, while substantial port facilities are available 15 miles away in the town of Pylos on the bay of Navarino. Regular measurements of water quality show transmission lengths of 55±10 m at a wavelength of 460 nm, stable temperatures of 14.2 °C and water current velocities well below 10 cm/s, light bursts of 1-10 s duration, consistent with bioluminescent activity, represent around 1% of the active time and there is little/no evidence of problems due to sedimentation or bio-fouling. The sea bottom over the site has a clay deposit accumulated over some tens of thousands of years which provides for good anchoring. The basic element of the NESTOR detector is a hexagonal floor or star. Six arms, built from titanium tubes to form a lightweight lattice girder, are attached to a central casing. Two optical modules are attached at the end of each of the arms, one facing upwards and the other downwards. The electronics for the floor is housed in a one-meter diameter titanium sphere within the central casing. The nominal floor diameter at the optical modules is 32 metres. A full NESTOR tower would consist of 12 such floors stacked vertically with a spacing of 30 m between floors. This is tethered to a sea bottom unit (pyramid) that contains the anchor, the junction box, several environmental sensors and the sea electrode that provides the electrical power return path to shore. The junction box houses the termination of the sea-end of the electro-optical cable, the fan-outs for optical fibres and power to the floors etc. as well as monitoring and protection of the electrical system. The optical module consists of a 15” diameter photomultiplier tube (pmt) enclosed in a spherical glass housing which can withstand the hydrostatic pressure up to 630 atmospheres. Other modules, above and below each floor, house LED flasher units that are used for calibration of the detector and they are controlled and triggered from the floor electronics. Deployed equipment is brought to the surface, together with the sea end of the electro-optical cable, by means of a recovery rope, released from the sea bottom by coded acoustic signal. Modifications or additions to the experimental package are made at the surface and all connections are made in the air with dry-mating connectors. The cable and experiment systems are then re-deployed and the recovery rope, with its acoustic release laid on the seabed. The NESTOR deployment ‘philosophy’ has always been to avoid the need for specialised manned or unmanned underwater vehicles for deployment and recovery operations that require the use of manipulators, wet-mating connectors and consequent high costs. All electrical and optical fiber connections are dry mated in the air. The objectives for the deployment reported in this paper were to test fully the electrical supply and distribution systems, the monitoring and control systems and the full data acquisition and transmission chain from the sea to the shore station (each NESTOR floor is independent from the others with respect to electrical power supply and data acquisition and transmission). The titanium girder arms of the stars are made in standard modules of 5-meter length; for logistical reasons on the deployment vessel, the star used for this experiment has an overall diameter of 12 metres. In all other respects standard equipment was used. The detector star is located 80 metres above the sea bottom pyramid. The system was powered and monitored during deployment while the pmts were switched on a few hours later when they had reached a quiescent state after brief exposure to daylight. The system was operated continuously for more than a month and several million triggers recorded. This has not only provided invaluable experience on the operation of the detector but has initiated the development and testing of powerful tools for reconstruction and analysis.

3. Data quality
In a typical example shown in Fig. 1, the pulse height distribution has a shape corresponding to a few (average 1.3) photoelectrons. The 40K background has been used as a stable ‘standard candle’ in order to monitor the gain stability of the detector. The pmt pulse height distributions from each data file were compared to a standard shape defined at the beginning of the run and found to be extremely stable for all of the pmts during the whole running period. However, there were periods of time when the instantaneous counting rates of a group of pmts and the collection trigger rate show a large increase which lasts up to a few seconds. These phenomena last typically from 1 to 10 sec and

Site coordinates: 36° 37.5’ N, 21° 34.6’ E
represent a total 1.1% of the active experimental time. The effect is consistent with bioluminescent activity from marine organisms in the detector vicinity. The pulse height distribution of the pmts during a period of bioluminescence is very similar to the distribution due to the $^{40}$K decay. Bioluminescence can be easily identified because of its characteristic time duration and therefore does not cause any background problem. In the analysis that follows, all events collected during periods of bioluminescence activity have been excluded. This represents a reduction of only 1.1% in the size of the data sample\(^3\). The average experimental trigger rate, corresponding to the coincidence of four or more pmt pulses above 30 mV amplitude, (corresponding to 0.25 of a photoelectron), was 3.76 Hz compared to an estimated rate of 3.79 Hz derived from the Monte Carlo simulations. According to the Monte Carlo estimation, only a small fraction (5.5%, 0.21 Hz) of this trigger rate corresponds to atmospheric muons passing close to the detector. When the pmt thresholds were set to 120 mV, (corresponding to one photoelectron), the measured trigger rate was 0.29 Hz, in agreement with the equivalent Monte Carlo estimate of 0.30 Hz. Furthermore, the measured coincidence rates, shown in Fig. 2, are in very good agreement with the Monte Carlo estimations for several levels of coincidence at different pmt thresholds. In the same plots, we present the Monte Carlo estimated contribution of the atmospheric muon flux to the triggers, showing that higher-level coincidences exclude the combinatorial background. A better rejection of the combinatorial background is achieved at higher pmt threshold values.

**Figure 1.** The pulse height distribution of a PMT during operation in deep sea (main plot) and from a calibration run in the laboratory (insert plot). The solid line in the main plot is the result of a fit to the data points using an exponential shape for the dark current (line a), as well as the one photoelectron (line b) and the two photoelectrons (line c) pulse height spectra evaluated during calibration runs at the laboratory.

**Figure 2.** Trigger rates as a function of the coincidence level, for two threshold settings. The points represent the data, the solid line the Monte Carlo estimation including background and the dashed line the Monte Carlo estimation for the contribution of the atmospheric muons.

### 4. Atmospheric muon studies

From the total data sample collected with a 4-fold or higher coincidence trigger and 30 mV pmt threshold, a subset containing 45800 events has been selected that have six or more pmt pulses (hits) within the 60 ns time window. These events have been analysed in order to reconstruct muon tracks. The arrival time of the digitized pmt pulses was used to estimate the muon track parameters by means of a $x^2$ fit whilst the pmt pulse heights were used to reject ghost solutions and poorly reconstructed tracks. The results are summarized here. The zenith angular distribution of the reconstructed tracks is

\(^3\) High levels of bioluminescence can cause severe dead-time in data taking. Note that in other Mediterranean sites, periods with more than 30% of bioluminescence activity has been observed.
compared to the Monte Carlo prediction in Fig. 3. Due to the limited reconstruction resolution, the distributions extend to zenith angles higher than 90°.

5. Conclusions
In March 2003, the NESTOR collaboration successfully deployed a test floor of the detector tower, fully equipped with final electronics and associated environmental sensors to a depth of 3800 m, situated 80 meters above the sea bottom station. The deployed detector was continuously operated for more than one month. The monitored experimental parameters, operational and environmental, remained stable within the accepted tolerances whilst the readout and DAQ chain performed well and with practically zero dead-time. The 1.1% of the total experimental time was lost due to bioluminescent activity around the detector. This 1% dead time is consistent with previous measurements in the same site done with autonomous drops. Events collected during such periods of activity were easily identified and rejected. Several studies have been made to ensure that the event selection trigger was unbiased and that the collected light on the pmts can be attributed to the expected natural sources. The pmt pulse height distributions, the trigger rates and the total number of photoelectrons inside the trigger window as functions of the signal thresholds and coincidence level settings as well as the arrival time distribution of the accumulated photoelectrons, agree very well with Monte Carlo predictions based on the atmospheric muon flux parameterization of Okada, on the natural 40K radioactivity in the sea water and the pmt dark currents and after pulses. In parallel, calibration in the sea using the LED flasher units mounted above and below the detector floor, provided a rigorous test on the time stability of the detector as well as a measurement of the resolution of the arrival time of the pmt signals. A subset of the accumulated data, consisting of events with six or more pmt pulses inside a 60 ns time window, has been analysed and the trajectories of atmospheric muons have been reconstructed. The distributions of the azimuth and zenith angles of the reconstructed muon tracks are found to be in a very good agreement with Monte Carlo predictions, based on the atmospheric muon model of Okada.

Finally, based on previous measurements by the NESTOR collaboration concerning the shape of the zenith angle distribution, we estimated the vertical atmospheric muon intensity at the deep-sea site. We parameterize the number of atmospheric muons \( N \) arriving at the detector depth per unit solid angle \( \Omega \), per unit time \( t \) and per unit area \( S \), \( dN/(d\Omega dt dS) \), as usual parameterized as \( dN/d\Omega dt dS = I_0 \cos^a(\theta) \) where \( I_0 \) is the vertical intensity. The measured vertical muon intensity and the index \( a \), at a depth of 3800 m.w.e., are \( a = 4.7 \pm 0.5 \) (stat) \( \pm 0.2 \) (syst) and \( I_0 = 9.0 \times 10^{-9} \pm 0.7 \times 10^{-9} \) (stat) \( \pm 0.4 \times 10^{-9} \) (syst) \( cm^{-2} s^{-1} sr^{-1} \) are in very good agreement with previous underwater measurements and with phenomenological expectations. The objectives for this deployment of the NESTOR test detector were to perform a thorough test of the electrical supply and distribution systems, the monitoring and control systems and the full data acquisition and transmission chain from the sea to the shore station. These objectives have been met successfully. In addition we have been able to demonstrate the ability of the proposed neutrino telescope to reconstruct muon trajectories.