Performance of the NESTOR Calibration System

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Abstract

The tracking performance of an underwater neutrino telescope depends mainly on the accurate determination of the arrival times of the Cherenkov photons that neutrino-induced muons emit to the optical sensors of the detector. That is the reason why the Calibration system of an underwater neutrino detector is of utmost importance. In this note, we describe the methods we used in order to perform time and gain calibration of the NESTOR detector during the 2003 Run.

1. Introduction

NESTOR (Neutrino Extended Submarine Telescope with Oceanographic Research) is a deep underwater neutrino detector, located in the Mediterranean sea, approximately 15 nm south-east of the coast of Pylos (Greece), at a depth of 4000 meters [1,2]. The basic detector unit is a rigid hexagon, made out of titanium with a diagonal of 32 m. At the tip of each arm of the hexagonal floor there is a pair of two 15 inch photomultiplier tubes (PMTs) inside benthos glass housings [3], one looking upward and the other downwards.
The electronics which are responsible for signal sensing, triggering, digitisation and data transmission to the shore are housed inside a large titanium sphere (1m in diameter) located at the center of the hexagonal floor. The electrical pulses of the PMTs are digitised by the Analog Transient Waveform Digitizers (ATWDs) [4] of the floor electronics board (Floor Board) developed at Lawrence Berkeley National Laboratory. The digitised waveforms are transmitted to shore, where the raw data are recorded. The Data Acquisition system is controlled from the shore by the Shore board, which in addition receives the digitised data and formats them according to the raw data protocol. All the environmental sensors, and the power supplies of the PMTs are controlled by another board in the titanium sphere (House keeping board), which in addition is responsible for the operation of the LED calibration system. By stacking 12 of these floors in the vertical, with a distance between them 30m, they create a tower shown in Figure 1, which is connected to the shore by an electro-optical cable (18 fibers plus 1 conductor). In March 2003, using the cable ship RAYMOND CROZE of France Telecom, a hexagonal floor was deployed fully equipped with electronics and associated environmental sensors to a depth of 4000m.

During the operation of the detector many calibration runs were performed. Three different systems were used for time and gain calibration: The LED calibration system, the analysis of the pulse height distributions in events collected during normal
data taking and the self-test operation of the Floorboard. In the following we describe the functions and the performance of these systems.

2. The LED Calibration System.

Each floor of the NESTOR detector has its own calibration system and can be operated separately from the shore. The Floor Calibration System (FCS) [5] uses LED flasher modules mounted above and below the detector floor at a distance of 20 m. The LED repetition frequency, the light amplitude as well as the duration of the calibration procedure are adjustable from the shore laboratory. The commands are transmitted from the Shore-board via the optical fiber to the Floor-board inside the titanium sphere [6]. Then the corresponding actions are taken to the House-Keeping board which is directly connected to the LED modules (Figure 2). Each LED is housed into a titanium cylinder leaving an opening angle for the light of about 40 degrees. Before deployment the system was tested at a pressure tank for several cycles to avoid operational failure in the deep sea.

Figure 2
The figure shows the calibration system for one Nestor floor (FCS). Two LEDs located at a distance of 20 m above and below the star, illuminate the up-looking and the down-looking PMTs respectively. The whole system is controlled from the shore by sending commands to the Floor board inside the titanium sphere.
2.1 Gain calibration

One of the most important characteristics of the LED system is its light angular profile. The light emitted by the LED was parameterised in units of the mean of the PMT pulse height distribution when only one photoelectron is emitted from the photocathode (single photoelectron distribution). This distribution is a Polya distribution:

\[ P(v; a, b) = \frac{(\frac{a}{b})^v}{v \cdot \Gamma(a)} e^{-\frac{a}{b}} \]  

(1)

where the parameters \( \alpha \) and \( b \) are related to the mean value \( \mu \) and the variance \( s \) of the distribution as: \( b = \mu \) and \( \alpha = \left( \frac{b}{\sigma} \right)^2 \)

LED flashes illuminated an array of PMTs with known single photoelectrons distributions. Then by adjusting the light intensity of the LED and measuring the recorded pulse height distribution we calculated the expected number of photoelectrons per light pulse for various light amplitudes.

![LED Angular Profile](image)

**Figure 3**

The LED output as a function of the angle with respect to the LED symmetry axis. The dots represent data taken at the laboratory during calibration tests. The parameterised angular distribution was used to estimate the angular profile of the LED in the water.
The characteristic light angular profile was measured at the lab where the optical medium surrounding the LED was air. The corresponding distribution in the water was estimated by means of Monte Carlo methods taking into account the PMT geometrical factor and the transmission factor of the light in the sea water [5] (Figure 3).

In deep sea the LED illuminated the PMTs with light corresponding to the single photoelectron conditions. The recorded pulse height distribution was compared with the Polya distribution measured at the lab in order to examine if the parameters $\alpha$ and $b$ (eq. 1) are the same (Figure 4).

![Figure 4](image)

*Figure 4*

*The pulse height distribution (crosses) during LED calibration runs at single photoelectron conditions. The data are fitted with an exponential (thermionic noise) and a Polya distribution (single photoelectron conditions). The estimated parameters $a$ and $b$ are compared with the values obtained during calibration at the lab.*

### 2.2 Time calibration

In a very large neutrino detector there are three things we must know in order to perform accurate time calibration:

1. The absolute time at the shore laboratory where the digitised pulses are recorded,
2. The delays of the signals during their propagation from the floor electronics to the shore laboratory, and
3. The delays of the signals during their propagation from the PMTs to the floor electronics.
For the test detector of the 2003 Run where a single floor was deployed, only the relative delays of the signals from the PMTs to the Floor board were needed [7]. Accurate time calibration was performed by measuring these relative delays from the PMT signals caused by the LED flashes. Taking into account that the LEDs were positioned equidistantly from the PMTs, the relative arrival time of the waveforms forced to be zero. For example in Figure 5 it is shown the relative delay of the pulses from two different (calibrated) PMTs, which were illuminated by the LED modules. The distribution exhibits a normal shape with zero mean value and variance equal to the quadratic sum of the transit time variation of the PMTs and the width of the light pulses.

![Figure 5](image)

**Figure 5**

*Relative timing distribution of two PMTs, obtained during calibration runs at the deep sea. The distribution exhibits a gaussian shape of zero mean and a sigma that includes the contribution of the TTS and the width of the light pulse.*

The accuracy of the timing calibration procedure described above depends on the amplitude of the pulses used in the analysis. This is due to the dependence of the Transit Time Spread (TTS) and the arrival time estimation on the amplitude of the pulses (slewing). Further analysis of the calibration data, resulted to in situ measurement of the TTS and the slewing correction. For example, in Figure 6 it is shown the variation at the PMT pulse arrival time as well as the Transient Time Spectra as functions of the PMT pulse amplitude as they have been estimated from the
calibration runs at a depth of 4000 m. The data were accumulated by varying the light output level of the LED system.

Since the PMTs are positioned symmetrically with respect to the LED flasher unit, the digitized PMT pulses (corresponding to all the up-looking or to all down-looking PMTs) are expected to exhibit the same arrival time, within measurement errors. The distributions of the arrival time difference between pulses of any pair of PMTs, produced by the same LED flash and with a pulse height greater than 800mV, show a peak at zero with a standard deviation compatible to the light pulse duration convoluted with the arrival time resolution. However, when we choose the pulses of the first PMT of the pair to have a lower than amplitude, the mean difference of the arrival times deviates from zero and the standard deviation of the distribution increases. The first effect is a result of the dependence of the arrival time definition on the pulse amplitude (slewing), whilst the second effect reflects the transient time spread and the pulse reconstruction resolution dependence on the amplitude of the pulse. These dependencies were measured using the calibration data and parameterised in order to be used in the track reconstruction analysis.

Figure 6
Slewing correction (left figure) and TTS (right figure) as a function of the pulse amplitude, estimated using calibration data taken during the detector operation at 4000m. They are found to agree very well with the measured ones from calibration runs in the LAB.

HOU-NS-TR-2004-02-EN
3. Calibration During Data Taking

3.1 The natural $K^{40}$ radioactivity

Sea water contains a small amount of potassium (0.038 ppm) which is composed of three isotopes, one of which is $K^{40}$ (0.0118%), a radioactive isotope with a half-life of 1.28 x 10^9 years. $K^{40}$ decays mainly via beta decay where the emitted electron have enough kinetic energy (above 240 keV) to produce Cherenkov photons in the water. This optical background due to $K^{40}$ beta decay plus the thermionic noise from the PMTs contribute to a baseline signal level of about 50 kHz per PMT [8]. Due to this constant rate of the PMTs, low level coincidence triggers (below 4 fold) originate mainly from the $K^{40}$ decays and not from muon tracks. These events can be used to study the characteristic pulse height distribution of the $K^{40}$ background source.

For example in Figure 7 it is shown a typical pulse height distribution of a PMT during data taking. The data were taken with a four-fold trigger condition (i.e. at least four pulses\(^1\) from different PMTs within the experimental time window). This distribution is very well described as the overlap of the thermionic background shape and the Polya distributions for one, two and three photoelectrons.

\(^1\) above a predefined threshold.
The pulse height distribution of one PMT using data from deep sea. The events were selected with a four fold coincidence trigger i.e. the majority of these events originates from the $K^{40}$ decays. The data are described with four different distributions: the PMT pulse height distribution due to the dark current and the distributions for one, two and three photoelectrons.

### 3.2 Atmospheric muons

When the coincidence level trigger is above 5 the main contribution to the global trigger rate originate from the light emitted by the atmospheric muons. The pulse height distribution of these events can be used to estimate the corresponding distribution when only one photoelectron is emitted from the photocathode of the PMT (equation 1). In case when $n$ phototoelectrons are emitted from the photocathode the corresponding pulse height distribution is the convolution of $n$ Polya functions:

$$P_n(v) = P(v;a,b) \otimes P(v;a,b) \otimes … \otimes P(v;a,b) = P(v;na,nb) \quad (2)$$

Consequently, the probability of a PMT pulse to be $v$ is:

$$P(V) = \sum_{n=1}^{\infty} R(n) \cdot P_n(V) \quad (3)$$

where $R(n)$ is the probability of having $n$ photoelectrons emitted from the photocathode.
Since the probabilities $R_n$ can be calculated with Monte Carlo simulation [9] the parameters $\alpha$ and $b$ for each PMT can be estimated from the corresponding pulse height distribution during data taking. For demonstration in Figure 8 it is shown the pulse height distribution of a PMT in events collected with six-fold coincidence trigger. The distribution is in agreement with the Monte Carlo predicted distribution, which is generated with the parameters $\alpha$ and $b$ estimated from the data.

![Figure 8](image)

*Figure 8*

*The pulse height distribution of a PMT (.crosses) during data taking with six fold coincidence trigger i.e. the majority of these events originate from atmospheric muons passing around the detector. The distribution is described accurately with the corresponding distribution predicted with the Monte Carlo simulation (histogram).*

4. Electronics Calibration

The Floor board electronics contain five 4-channel ATWDs which digitise the PMT waveforms and the clock signals. Even if the PMTs are well calibrated, the digitisation procedure may contribute to the degradation of the timing resolution due to the instability of:

- The gain of the ATWDs
- The ATWD sampling rate.
- The offsets of the ADC channels.

In order to monitor the gain, the Floor board electronics produce a standard known pulse that is digitised simultaneous from all the PMTs. By comparing these
waveforms with the standard pulse, the gain of the ATWDs can be estimated (Figure 9).

![Figure 9](image)

The gain of the 8 ATWD channels that digitise the PMT waveforms.

The ATWDs of the floor board consist of 128 10-bit Wilkinson ADCs. The transformation of the sample number (0-127) into time is performed if we know exactly the sampling interval of each ATWD channel. The sampling interval can be estimated from the digitized clock signal, which has known frequency. If we assume that $\delta n$ is the number of samples that cover $N$ periods ($T$) of the clock signal then the estimation of the sampling interval is $t_s = \frac{N \cdot T}{\delta n}$. In Figure 10 is shown the estimated sampling interval of an ATWD during a run. The root mean square of the distribution is about 6 ps.

Finally the offsets of the ADCs must be subtracted from the digitised waveforms before any processing. These offsets can be estimated for a specific ATWD by selecting events with not any signals in the corresponding PMT.
5. Performance of the Calibration Systems

The performance of the calibration systems can be demonstrated by direct comparison of Monte Carlo predictions and data distributions [10,11,12,13,14]. The sample we used was collected with 6-fold coincidence trigger logic, which originates from muon tracks passing near the detector. The pulses were analysed with the standard signal processing procedures [15] in order to estimate the arrival time and the pulse height in units of the mean of the single photoelectron distribution using the information from the calibration database.

For example in figure 11 is shown the distribution of the total number of photoelectrons per track as well as the time residuals distribution. It is clear evidence the excellent agreement of both distributions proving the success of the NESTOR calibration system.
6. Conclusions

In this note we described the way that calibration can be performed in the deep sea. The NESTOR LED calibration system was used for the PMT gain and timing calibration while the electronic generated pulses were used for monitoring the gain and the offset of the ADC channels and the sampling rate of the ATWDs. In addition it was demonstrated that the pulse height distributions of the PMTs in events originating from the accidental decays of $K^{+0}$ or from the atmospheric muons at the detector depth could be used for calibration purposes as well.

Acknowledgments

The authors of this note wish to thank the members of the NESTOR collaboration, the stuffs of the NESTOR Institute as well as the academic and technical personnel of the School of Science and Technology of the Hellenic Open University for their help, scientific, technical and financial support.
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