Time over Threshold electronics for an underwater neutrino telescope

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Abstract
The use of time over threshold (ToT) digitization techniques for the treatment of the output signals of the photomultiplier tubes (PMTs) of the KM3NeT detector is under consideration by the KM3NeT consortium. In this technique the leading and trailing edge of the signal above a certain threshold are time stamped and the corresponding times are sent to the onshore acquisition system. More information can be obtained by applying the same scheme at multiple threshold levels. In this note, we present the efficiency of such a digitization technique applied to signals provided by the HELenic Lyceum Cosmic Observatories Network (HELYCON) extensive air shower detector. We describe the operation and performance of these electronics and we evaluate the reconstruction accuracy of PMT signals using data collected from Extensive Air Showers of Cosmic Rays. Finally, we report on our plans to use this electronics in Optical Modules proposed for KM3NeT.

1. Introduction

The Time over Threshold (ToT) technique is being considered by the KM3NeT [1] collaboration for the digitization of the signals of the telescope’s photomultipliers (PMTs), since this would require only a small amount of off-shore electronics, thus minimizing power consumption and maximizing reliability [2]. The technique is based on the time-tagging of the leading and trailing edge of the signal above a number of certain thresholds. These time values are then used for the reconstruction of the PMT pulses. The hardware used has been designed by the Hellenic Open University (HOU) group and it is based on a high precision time to digital converter (HPTDC) chip developed at CERN and offering up to 32 channels with a digitization accuracy of 100 ps.

The sea-water neutrino telescope KM3NeT is briefly described in sections 2 and 3. We present the characteristics and operation of the electronics board developed for the implementation of the technique as well as the setup adopted for the board and ToT technique testing. The testing procedure was based on PMT signals generated by a HELenic Lyceum Cosmic Observatories Network (HELYCON) [3] detector, as described in section 4. The HELYCON detector stations have also been proposed for the calibration of a deep-sea neutrino telescope [4], [5]. The performance of the board and the accuracy of the reconstruction of the PMT signals are presented in section 5.

2. Neutrino telescopes

Neutrino telescopes aim at studying the Universe using neutrinos. Amongst the main neutrino telescope objectives are the discovery and study of neutrino sources like supernova remnants, pulsars and micro-quasars in the Galaxy, as well as extragalactic sources like active galactic nuclei and γ-ray burst emitters. The respective neutrino energy scale is $10^{12}$ to $10^{16}$eV. Another important objective is the search for dark matter in the form of WIMPs (Weakly Interacting Massive Particles). In addition, the study of the diffuse neutrino flux, originating from sources that cannot be individually resolved or from interactions of cosmic rays with intergalactic matter or radiation, may yield important cosmological clues. The neutrino energies in this case are above $10^{13}$eV. The fluxes of neutrinos of the mentioned processes require detectors of very large volumes of the order of a cubic kilometer so as to have the adequate sensitivity.

The most widely used neutrino detection technique is the detection of the Cherenkov light (Fig. 1) emitted from muons and hadrons produced by neutrino interaction with matter in large volumes of water or ice. Another technique is based on liquid scintillators and streamer tubes that detect charged particles. Recently, experiments are being developed for the detection of radio waves or sound produced in neutrino interactions.

The kilometer-scale requirement for neutrino detectors based on the detection of Cherenkov light requires the use of naturally occurring volumes of water or ice. Due to their better optical properties, deep sea-water telescopes bear significant advantages over the ice and lake telescopes. However, the deployment and operation of such neutrino telescopes faces serious technological challenges.

DUMAND [6] was the first experiment that tried to deploy a deep sea-water telescope. AMANDA [7] and BAIKAL [8] deployed operational detectors from the surface of solid glacial ice and from the frozen surface lake ice. After the completion of the AMANDA detector the collaboration proceeded with the construction of a much larger detector, the IceCube [9] which is expected to be completed by 2010.

Sea-water neutrino telescopes exhibit significantly better angular resolution (down to 0.1° for sea-water compared to approximately 1° for IceCube) and a more uniform efficiency due to the homogeneity of the medium. On the contrary, sea-water neutrino telescopes suffer from higher optical background due to radioactive decay of $^{40}$K and bioluminescence (light emission from living organisms). These backgrounds can be mitigated in...
the design of the detector by having a high density of optical modules and local coincidence triggering or a high-bandwidth data readout.

The pioneering work of DUMAND to build a deep sea neutrino telescope is being continued in the Mediterranean Sea by ANTARES [10], NEMO [11] and NESTOR [12]. These three projects have demonstrated the potential of the Cherenkov detection technique by reconstructing the tracks of muons, the possible reaction products of the sought-after neutrinos. These projects have provided a wealth of information on the technologies required for a large deep sea neutrino telescope.

3. KM3NeT

KM3NeT is a future deep-sea research infrastructure hosting a neutrino telescope with a volume of at least one cubic kilometre to be constructed in the Mediterranean Sea. KM3NeT will take advantage of the achievements of the deep-sea neutrino projects mentioned in the previous section. The geographic location of the Mediterranean Sea is ideal since the region of the sky observed by a neutrino telescope would include the centre of the Galaxy. The design, construction and operation of the KM3NeT neutrino telescope is pursued by a consortium formed around the institutes currently involved in the ANTARES, NESTOR and NEMO pilot projects. Based on the leading expertise of these research groups, the construction of the KM3NeT telescope is being planned to start in 2011.

The KM3NeT neutrino telescope is composed of a number of vertical structures (the “Detection Units”), which are anchored to the sea bed and usually kept vertical by one or several buoys at their top. Each detection unit carries photo-sensors and devices for calibration and environmental measurements, arranged vertically on “Storeys” carrying electronics with interfaces to power supply and data transmission lines. The basic photo-sensor unit is an “Optical Module (OM)” housing one or several photomultiplier (PMT) tubes, their high-voltage bases and their interfaces to the data acquisition system with nanosecond timing precision. In each detection unit the data and power flow proceed vertically and is connected via the anchor to a deep-sea “Cable Network”. This network typically contains one or more junction boxes with one or several electro-optical cables to shore, through which the OM data are transferred for on-shore processing. The network also provides power and slow-control communication to the detector. A “Shore Station” with substantial computing power is required for collecting the data, applying online filter algorithms and transmitting the data to mass storage devices. The overall setup is schematically depicted in Fig. 2.

Two detection unit designs were chosen to be pursued. The first option is the “string” design with single, large photo-cathode area or multi-PMT OMs on each storey. The OMs are mechanically connected to the cable via a minimal structure. The mechanical part of the cable structure is continuous. Alternatively a “tower” design is being considered in which detection units are composed of relatively compact, transportable horizontal structures that are connected to each other by mechanical cables to form a flexible tower. The cabling for power and data transport is separated from the mechanical cabling. Optical modules are attached to the edges of the horizontal structures.

The read-out of the PMT signals will be either all-optical or copper/optical in both design options.

3.1 Readout System Bandwidth Requirements

The main purpose of the readout system is the conversion of the analogue outputs of the PMTs into formatted data for offline analysis. The deep sea infrastructure will also contain a large number of instruments for various scientific research activities. The operation of these instruments will be incorporated in the general readout system of the infrastructure.

The preferred solution for the readout system for KM3NeT is one where all (digitised) data are sent to shore, for processing in real-time.

For a total effective photo-cathode area of 50 m^2·sr, the required bandwidth amounts to about 0.1 Tb/s, with 8 Bytes per recorded photon. This data rate to shore can be
accommodated on a reasonable number of optical fibres with standard telecommunications protocols using either coarse or dense wavelength division multiplexing.

The total data rate exceeds that of any data storage capacity by several orders of magnitude. Hence, the raw data have to be filtered, meaning that the rare neutrino (muon trajectory) signals must be discriminated from the random background. The total data rate from the submarine infrastructure must be reduced by a factor of 10000 to less than 10 Mb/s, so that the data can be transferred to the various computing centres in real-time for storage on permanent media.

The high level of reliability of the deep-sea infrastructure - mandatory due to the high cost of off-shore repair and maintenance operations - can be enhanced by reduction of the number of active components, the adoption of large design margins and the utilization of robust and redundant network topologies.

### 3.2 Photomultiplier Readout

The analogue signals produced by each PMT must be encoded by the front-end electronics in a way suitable for transmission to shore and subsequent processing. The encoding is aimed at extracting the relevant information from the raw analogue signal. A time stamping operation is necessary and can either be implemented after the transmission of data to shore, “on-shore”, or “off-shore” in the front-end electronics. It is envisaged to implement the front-end electronics inside the optical module.

Various options are possible for the implementation of the front-end electronics including analogue transmission, continuous sampling and self-triggering.

While analogue sampling transmission can be considered the ideal scenario, for large distances to shore the original signals would deteriorate too severely; this option is not being pursued.

In the other options the analogue signal is converted to digital data. The continuous sampling option aims at extracting as much information as possible from the analogue pulse. In general, this option requires the largest bandwidth. The required bandwidth is determined by the sampling frequency (typically 200 MHz) and the dynamic range of the analogue to digital converter (typically 8 bits) used to convert the instantaneous pulse height to a digital value. The data can be reduced by applying a zero-skipping mechanism. The traditional solution is based on a self-triggering system (e.g. a threshold crossing) in which the signal is time stamped using a time-to-digital converter (TDC) and the total charge is measured by an analogue-to-digital converter (ADC). The typical threshold is 0.3 of the level of a single photoelectron pulse (spe). A possible implementation of this concept could be via an Application-Specific Integrated Circuit (ASIC) as for the ANTARES experiment. The main functions that should be integrated in the design of this new device are pulse shape discrimination, timing, integration of the charge of the signals and analogue to digital conversion. An alternative implementation could consist of using commercial ADCs and field programmable gate arrays (FPGAs). Most of these incorporate data buffering for the efficient transfer of data.

The continuous sampling of a time-over-threshold signal is, however, also under consideration, as described in the following section. Such a design would require a small number of off-shore electronic components, thus minimising power consumption and maximising reliability.

### 4. Time Over Threshold

The ToT technique is based on the use of a time to digital converter (TDC) that performs time-tagging of the leading and trailing edge of the PMT signal above a certain threshold. More information can be obtained by applying the same scheme at different threshold levels. This gives the same information as the continuous sampling solution discussed in the preceding section. Analogue signals pass through comparators which compare them with the desired thresholds. The outputs of the comparators are then fed to the TDC that performs the time-tagging of the leading and trailing edges. These values are subsequently used for the reconstruction of the pulse shape and its charge. Applying the scheme to multiple thresholds increases the efficiency of the technique significantly.

![Fig. 3. The HELYCON ToT data acquisition board](image)

#### 4.1. Time Over Threshold Readout electronics

The HELYCON ToT data acquisition board (Fig. 3) is based on a high precision time to digital converter (HPTDC) chip developed at CERN [13]. The schematic representation of the board is depicted in Fig. 4. The HPTDC accuracy is 25ps with 8 channels, while with 32 channels it is 100ps. The latter is the mode employed for the board, allowing for 6 channels per input, which correspond to 6 threshold values for each input signal. Each of the board’s 5 signal inputs is driven to a set of 6 comparators after being amplified by a certain factor. The current version of the board exhibits different
amplification factors (scale) of 1, 1, 1.5, 2.5 and 5, so that the best option can be selected, balancing the desire for a higher scale that will allow the recording of small pulses, with that for a smaller scale that will allow the recording of larger pulses. The outputs of the comparators are driven to the HPTDC, which performs the time-tagging of the threshold crossings. The time values from the HPTDC along with a GPS time reference signal are then driven to the FPGA, which incorporates filter algorithms, the trigger logic and event-building algorithms. A USB controller handles the communication between the FPGA and the hosting computer. The power consumption of the HPTDC is around 0.5W, while the current version of the board has a power consumption of around 15W, which can be substantially reduced for the final version of the board.

Specially developed software allows the user to enable and disable individual threshold levels, to set the values of active thresholds, and run basic calibration processes on the channels.

4.2. Set-up and operation

Extended testing has been performed for the determination of the characteristics of the electronics (such as the exact values of the input scales and channel offsets), the evaluation of the board performance and of the PMT signal reconstruction accuracy. The testing configuration chosen was based on the signal of the PMT of a HELYCON detector and is depicted in Fig. 5. The signal was split twice and fed to the board as well as to a high precision oscilloscope (of a sampling rate of 5GS/s). The signal was also sent to a discriminator whose output was used to trigger the oscilloscope and was also recorded by the HELYCON DAQ board. Thus, the identification of PMT pulses recorded by both the oscilloscope and the board can be achieved, so that they can be compared.

5. Photomultiplier signal charge estimation

5.1. Board characteristics

Before attempting to reconstruct the PMT signal, a number of characteristics of the board had to be determined. These include the exact values of the scales for each of the board’s analogue inputs, the offsets of each of the channels (a total of 30 channels, namely 6 channels for each analogue input), the noise of each channel and the minimum threshold that can be applied to each of the channels (taking into account the respective noise level).

In order to do so, a DC voltage of the order of a few mV was applied to each of the board’s inputs. The software’s built-in “Calibrate DC” procedure was used, which increased the threshold for each channel by the minimum step (0.833mV), spanning the area defined by the user, saving the number of threshold crossings for
each threshold value. The result is a Gaussian with mean the DC voltage applied to the input multiplied by the input’s scale plus the channel’s offset. The Gaussian’s sigma value indicates the noise of each channel. By applying different values of DC voltage to the inputs, the scale (multiplication factor) of each input and the offset of each channel was determined.

Concerning the noise of the inputs, the minimum threshold that can be applied is 1.57mV for the 2.5 scale input. This corresponds to around 1/3 of the Minimum Ionizing Particle (MIP) signal size for the HELYCON detectors and is a very good tool for the timing analysis of the recorded pulses. The highest threshold for this board input is 800mV (150-200MIP) but, of course, much higher pulses can be reconstructed using the times over threshold information\(^1\). The 5 scale input exhibits slightly lower (and the lowest among the 5 inputs) minimum threshold (1.42mV), but the higher threshold that can be applied to it is only 400mV decreasing the accuracy of reconstruction for larger pulses. Thus the 2.5 scale has been selected for the final version of the board.

Fig. 6 depicts a typical HELYCON detector pulse (that corresponds to around 10 MIPs) as recorded by the oscilloscope (line), while the dots correspond to the threshold crossings recorded by the board.

Fig. 6. A typical HELYCON detector pulse as recorded by the oscilloscope (line) and by the HELYCON board (dots)

### 5.2. Charge estimation

For the evaluation of the charge estimation efficiency of the ToT technique, extensive air shower cosmic ray data from a HELYCON detector - collected with a high sampling rate oscilloscope - have been used for the generation of the ToT values corresponding to a set of thresholds (namely 3mV, 10mV, 20mV, 40mV, 70mV and 100mV). Subsequently, the plots of the measured charge versus the sum of the times over threshold were generated for the areas where 1, 2, 3, 4, 5 and 6 thresholds were crossed (all the areas are depicted in Fig. 7). The lowest threshold was set to about half of the mean pulse height of a MIP signal. The choice of these thresholds allows the reconstruction of higher pulses with good accuracy, while at the same time the smaller pulses (1-2MIPs) are reconstructed with acceptable accuracy, as shown below.

Fig. 7. The measured charge as a function of the sum of the times over threshold.

Fig. 8. The measured charge minus the estimated charge divided by the measured charge in the case that 4 thresholds have been crossed.

Parameterizations were calculated for each of the areas (usually in the form of a polynomial function), that were then used for the calculation of the charge of the pulses by using the values of the times over threshold. By comparing the calculated charge versus the measured charge, the charge estimation resolution can be evaluated. Fig. 8 shows the distribution of the measured charge minus the estimated charge divided by the measured charge for the case that four of the thresholds have been crossed. The estimated resolution in this case turns out to be 4.3%. The respective pull distribution is depicted in Fig. 9 and exhibits a sigma of 1.04±0.07 that proves that the estimation is unbiased.

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\(^1\) Pulses exceeding the 800mV limit are not distorted but just truncated by means of a zener diode
Fig. 9. The measured charge minus the estimated charge divided by the estimated error in the case that 4 thresholds have been crossed.

Fig. 10. The charge estimation resolution (%) versus the number of thresholds crossed.

Fig. 10 depicts the charge estimation resolution versus the number of thresholds crossed. Of course, as the number of thresholds crossed increases, the resolution gets better. In the case all 6 thresholds have been crossed, the resolution seems worse because the highest pulses have been truncated by the oscilloscope, which was setup to record pulses up to 150mV with the best resolution.

The work for the evaluation of the ToT technique and its application on the data recorded by the HELYCON board is ongoing. More threshold values combinations have to be examined and tested on the board and effective algorithms developed for double pulses separation. However, a choice of thresholds that are more closely spaced near the baseline will allow the reconstruction of smaller pulses with reasonable accuracy, while higher pulses will still be reconstructed with good accuracy even though the crossed thresholds do not go very far up the pulse height.

6. Conclusions

The ToT technique exhibits a charge estimation resolution down to 3-4% for the specific choice of thresholds mentioned in section 5.2 and pulses of the order of 70mV and higher. This pulse height corresponds to around 14MIPs for the HELYCON detector. The achieved resolution is sufficient for the HELYCON experiment and will be the same for KM3NeT neutrino telescope signals of the same level. However, additional work must be done for the optimum choice of the threshold levels for the application of the ToT technique on the PMT signals of the KM3NeT neutrino telescope.

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References