Use of floating surface detector stations for the calibration of a deep-sea neutrino telescope *

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Abstract We propose the operation of floating Extensive Air Shower (EAS) detector stations in coincidence with the KM3NeT Mediterranean deep-sea neutrino telescope to determine the absolute position and orientation of the underwater detector and to investigate possible systematic angular errors. We evaluate the accuracy of the proposed calibration strategies using a detailed simulation of the EAS and KM3NeT detectors.

Keywords: KM3NeT, Calibration, Extensive air showers

1 Introduction

The KM3NeT consortium is currently working on a conceptual design for a future Mediterranean neutrino telescope, which will have an instrumented volume of a scale of 1 km$^3$ [1]. A floating array of Extensive Air Shower (EAS) detectors can be used as a seafloor calibration infrastructure, on top of the KM3NeT neutrino telescope. Such an array can detect the copiously produced, low energy and small zenith angle, atmospheric showers and the collected data can be used for the reconstruction of the direction and of the impact parameter of the shower axis. The EAS detector array used in this study consists of floating HELYCON (HEllenic LYceu Cosmic Observatories Network) scintillation counters [2].

According to Monte Carlo studies, presented in this paper, 35% of the cosmic showers in the energy range of $10^{14} - 5 \times 10^{15}$ eV contain energetic muons able to penetrate the sea water and reach the KM3NeT detector. These muons are detectable by the deep-sea telescope and the muon track parameters can be estimated with high accuracy. The comparison of the reconstructed muon track parameters with the direction and the impact of the shower axis can be used in order to (a) reveal systematic angular errors in the determination of the track parameters by the neutrino telescope and (b) provide an absolute positioning of the undersea detectors.

2 Helycon

2.1 Description

The HELYCON EAS detector array consists of detector stations distributed over western Greece. Each station consists of charged particle detectors, a GPS antenna, digitization and control electronics, as well as a data acquisition system controlled by a personal computer. The collected data are broadcasted through the Internet to a main counting room, while the synchronization between the HELYCON stations relies on the GPS time-signal. A single station is able to detect atmospheric showers initiated by cosmic particles of energy more than $10^{14}$ eV.

The HELYCON charged particle detector is a scintillation counter of 1 m$^2$ active area. It is made of plastic scintillator tiles wrapped in Tyvek reflective paper, while the light is collected by wave shifting fibers embedded inside the grooves of the scintillating tiles and it is detected by a fast photomultiplier tube.

The HELYCON Readout [3] card utilizes the High Precision Time to Digital Converter (HPTDC) chip, designed at CERN [4], and offers up to five analog inputs, each one for a scintillation detector. The input signals are compared to six predefined (remotely adjustable) thresholds and the corresponding times of the PMT waveform-threshold crossings are digitized with an accuracy of 100 ps by the HPTDC. The trigger is realized in the Field Programmable Gate Array (FPGA) of the Readout card which is also responsible for formatting the data and for communicating with the station (local) PC. The data are saved on the hard disk of the local computer and transmitted on request, via the Internet, to a central server.

2.2 Calibration and performance

The charged particle detectors, before their commission, undergo several evaluation tests and calibration procedures, including the calibration of the photomultiplier tubes, measurements of the response of each detector to a minimum ionizing particle (MIP), evaluation of the uniformity of each detector response with respect to the MIP incident point, as well as the synchronization of all detectors belonging to the same HELYCON station.

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The charge distribution of an active HELYCON detector in a shower event. (Figure 1)

The performance of HELYCON in detecting and reconstructing showers has been studied by operating a system of eight detectors in the laboratory. Two of the detectors were used in coincidence in order to define an event selection trigger, while the waveforms of the other six detectors, divided in two groups A and B, were digitized. The collected experimental data were compared to simulation predictions. In particular, the CORSIKA air shower simulation software [5] was used to produce air showers, initiated by cosmic protons entering isotropically the upper atmosphere, whilst the detector response was simulated by the specific HELYCON MC package. The events produced by the simulation were stored using the same format as the experimental data and were analyzed as real events.

A detector was considered to be active if its signal exceeded in charge the signal corresponding to four MIPs. Subsequently, an event was considered as a candidate of a shower event if at least one of the detector groups A or B was active. Fig. 1 demonstrates the success of the simulation package to describe the charge distribution of an active detector in a shower event.

In order to evaluate the performance of a typical HELYCON station, the analysis focused on the subset of events in which all six detectors were active. The axis direction of every single one of the above events was reconstructed by using (a) all six detectors, (b) only the group of detectors A and (c) only the group of detectors B. The direction of the shower axis was reconstructed by using the relative arrival times of the detector signals and implementing a simple plane-wave hypothesis for the shower front. In the case of MC analyzed events, the possibility exists for a direct comparison of the reconstructed to the generated zenith angle values revealing the angular resolution of each detector setup. The corresponding resolution values for the detector group A, detector group B and all six detectors are

$\sigma_{MC}^A = 4.5^{\circ} \pm 0.5^{\circ}$, $\sigma_{MC}^B = 5.2^{\circ} \pm 0.6^{\circ}$

$\sigma_{MC}^6 = 3.5^{\circ} \pm 0.3^{\circ}$

One can also evaluate the HELYCON station resolution, solely from the real data, by comparing the results obtained by the two detector groups (A and B) on an eventbyevent basis. Fig. 2 presents the distribution of the difference ($\Delta \theta = \theta_A - \theta_B$) of these two estimated values of the zenith angle. The histogram corresponds to the MC prediction while the solid curve represents a Gaussian fit to the data points, with a sigma parameter, $\sigma_{DATA} = 7.2^{\circ} \pm 0.2^{\circ}$. This spread is consistent with the MC prediction for the resolution of each detector group

$\sigma_{MC} = \sqrt{(\sigma_{MC}^A)^2 + (\sigma_{MC}^B)^2} = 6.9^{\circ}(\pm 0.5^{\circ})$

3 KM3NeT calibration with HELYCON detector arrays

3.1 Calibration set-up

The analysis of atmospheric showers observed in coincidence by the Antarctic Muon and Neutrino Detector Array (AMANDA) [6] and the South Pole Air Shower Experiment (SPASE) [7] resulted in the calibration and survey [8] of the deep AMANDA detector. In the case of a deep-sea neutrino telescope, as the Mediterranean KM3NeT, a cosmic shower array on the nearby shore cannot be used for calibration purposes. However, a floating HELYCON detector array on top of the neutrino telescope can be used to calibrate the deep-sea detector. This array employs the copiously produced, low energy and small zenith angle, atmospheric showers. According to Monte Carlo studies, 35% of the cosmic showers in the energy range of $10^{14} - 5 \times 10^{15}$ eV contain energetic muons (E>2 TeV) able to penetrate the 4000m deep-sea water and reach the KM3NeT detector. Moreover, the two-thirds of these muons can be reconstructed by the neutrino telescope and their direction can be evaluated with an accuracy of 0.15°.

The calibration capabilities of three autonomous HELYCON detector arrays on floating platforms were quantified by a Monte Carlo study using (a) CORSICA to simulate EAS, (b) the HELYCON detector simulation package and
Figure 2: The distribution of the difference of the two detector group estimations. The solid curve represents a Gaussian fit to the data points, while the histogram corresponds to the simulation prediction.

(c) KM3Sim [9] a GEANT4 [10] based simulation package to describe the passage (energy losses, electromagnetic shower production, multiple scattering, Cherenkov light emission) of muons through the water and the operation of a large underwater neutrino telescope. In this study the platforms, equipped with a dynamic positioning system, were assumed to float 4000m above the neutrino telescope, 150m apart of each other, around the vertical symmetry axis of the telescope. Each platform contained 16 HELYCON detectors, arranged on a two-dimensional grid (5m×5m cell size) covering an area of about 360 m$^2$. It was assumed that every single floating detector array was operated independently from the others, as an isolated detector.

In this study, the neutrino telescope was assumed to have the IceCube hexagonal geometry [11], while the Optical Module (OM) consisted of 40 cylindrical PMTs 3 in. diameter inside a 17 in. benthos sphere, covering 4π in solid angle [12]. This study is based on the assumption that the relative positions of the OMs of the KM3NeT are known by using for example acoustical positioning techniques. The simulated response of the neutrino telescope to down-coming muons, produced in the EAS, was used to estimate the muon track parameters.

3.2 Investigation for a systematic angular offset

The simulated response of each HELYCON detector array to EAS was analyzed in order to reconstruct the direction of the shower axis, as described in Section 2, employing only detector signals from the same detector station. A minimum of three active detectors, each with a signal exceeding four MIPs, was required to define an event as a shower event candidate. Any shower event that contained at least one energetic muon reconstructed by the neutrino telescope was used in the calibration and the estimated zenith angles of the shower axis and of the muon track were compared on an event by event basis. The difference between these two angles should follow a normal distribution with mean value equal to zero. Any statistical significant deviation of this mean value from zero indicates that the estimations of the neutrino telescope suffer from a systematic angular offset. The sigma parameter of the Gaussian fit expresses the calibration resolution per shower.

The calibration resolution per single shower decreases when events with more active detectors are selected, as shown in Fig. 3, because the reconstruction accuracy of the showers direction improves. However, the requirement of more active detectors per event results to a reduction in the effective area of the floating detector array. The calibration resolution, scna, in identifying a possible angular offset in the neutrino telescope estimations using the three floating detector arrays, is approximated by the following equation:

$$
\sigma_{c}(n_a) = \frac{\sigma_{1}(n_a)}{\sqrt{N}} = \frac{\sigma_{1}(n_a)}{\sqrt{3<E_{\text{eff}}(n_a)>} \int_{\Delta E} \Phi(E) dE \Delta T}
$$

where na is the minimum number of active detectors per shower event, $\sigma_{1}(n_a)$ is the calibration resolution per single shower, N is the total number of shower events containing energetic muons reconstructed by the HELYCON detector arrays and the neutrino telescope, $< A_{\text{eff}}(n_a) >$ is the averaged over energy effective area of one detector array, $\Phi(E)$ is the cosmic ray differential flux, $E$ is the cosmic ray energy and $\Delta T$ is the time of operating the three floating detector arrays. Fig. 4 shows this calibration resolution for 10 days of operation, for different event selection criteria, demonstrating that the proposed calibration system will be able to measure a possible zenith angle offset with an accuracy of 0.05°. Furthermore, shower events with less than five active detectors do not contribute significantly in the calibration performance of the floating arrays.

\footnote{In this estimation the effect of the platform inclination due to winds and waves has not been taken into account. However, this is not a problem since the platform inclination can be accurately measured using a high precision tiltmeter on the platform. Commercially available digital tiltmeters can offer an accuracy much better than 0.05°.}
Figure 3: The calibration resolution per single shower as a function of the number of the minimum active detectors in the shower event.

Figure 4: The calibration resolution of three HELYCON detector arrays, for 10 days of operation, as a function of the minimum number of active detectors per event.
3.3 Estimation of the KM3NeT absolute position

The absolute position of the underwater telescope can be also measured using the floating HELYCON detector arrays. The technique is based on measuring the distance, on an event-by-event basis, between the impact points of the reconstructed muon track and the shower axis on the sea surface. The accuracy of this calibration technique can be quantified by a similar expression as Eq. (1). The position calibration resolution per single shower ranges from 2035 m depending on the number of active detectors. Assuming that the position of the floating array is known with accuracy much better than this resolution, the operation of three floating detector arrays, collecting data for 10 days, can provide an estimation of the absolute position of the neutrino telescope with an accuracy of about 0.6 m.

4 Conclusions

Detailed Monte Carlo studies, presented in this paper, have shown that three floating HELYCON detector arrays can measure a possible angular offset in the neutrino telescope estimations with an accuracy of 0.05°, while the absolute position of the underwater detector can be estimated with an accuracy of about half a meter.

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