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## Absolute angular calibration of a submarine km<sup>3</sup> neutrino telescope

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### ABSTRACT

A requirement for neutrino telescope is the ability to resolve point sources of neutrinos. In order to understand its resolving power a way to perform absolute angular calibration with muons is required. Muons produced by cosmic rays in the atmosphere offer an abundant calibration source. By covering a surface vessel with 200 modules of 5 m<sup>2</sup> plastic scintillator a surface air shower array can be set up. Running this array in coincidence with a deep-sea km<sup>3</sup> size neutrino detector, where the coincidence is defined by the absolute clock timing stamp for each event, would allow absolute angular calibration to be performed. Monte Carlo results simulating the absolute angular calibration of the km<sup>3</sup> size neutrino detector will be presented. Future work and direction will be discussed.

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### 1. Introduction

The aim of this report is to describe work done towards the feasibility study of using DELTA BERENIKE, a surface vessel, as a platform for an air shower array. The array is to be used for the absolute angular calibration of the deep km<sup>3</sup> size neutrino telescope. A vital requirement of a viable marine neutrino telescope is the ability to resolve point sources of neutrinos. The telescope functions by reconstructing neutrino-induced muons. In order to understand the resolving power of the instrument, an absolute angular calibration in muons is required. Muons produced by cosmic rays in the atmosphere offer an abundant calibration source.

DELTA BERENIKE is a triangular surface vessel designed for the deployment of deep-sea structures of a neutrino telescope. By covering the surface of the vessel with 200 5 m<sup>2</sup> plastic scintillator modules, a surface air shower array can be set up. Running this array in coincidence with a deep-sea km<sup>3</sup> size neutrino detector, where the absolute clock-timing stamp for each event defines the coincidence, would allow for performing the required absolute angular calibration.

The technique of using a surface air shower array made up of plastic scintillator modules to calibrate a neutrino telescope has been considered already [1–3]. However, the novel approach here is that the reconstruction of the muon tracks needs to be performed only for the KM3NeT data, i.e. there is no need to reconstruct the shower direction with the surface array but one

can use the position of the surface array as a “source” of muons. Knowing the location of DELTA BERENIKE from the ship's GPS receivers will allow the use of simple geometry to determine the true ship-KM3NeT direction. Additional filtering would be possible by reconstructing the direction of air showers, triggering both DELTA BERENIKE and KM3NeT.

All simulation and reconstruction work reported here has been conducted within the SeaTray [4] framework.

### 2. Muon production

Muon sample files were produced using the CORSIKA Monte Carlo code for the simulation of cosmic rays showers in the atmosphere and the generated muon bundles were propagated to the KM3NeT detector at various depths: 3500, 4500 and 5000 m. Geant4 [5] code was used to simulate secondary particle production for each muon track as well as Čerenkov photons. The output of the Geant4 module was used to generate hits in the optical modules of the km<sup>3</sup> size detector. The canonical km<sup>3</sup> size detector used for the present simulation is the String Design with Multi-PMT optical modules. The parameters were as follows:

- 154 strings in a hexagonal grid with string-to-string distance 95 m;
- height of lowest storey 100 m above sea floor;
- number of storeys 20;
- distance between storeys 30 m;
- 3" PMTs with QE 42%;
- 31PMTs per OM; orientation as defined in string design writeup v3.4 (NIKHEF) [6];

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- angular acceptance as defined in WP2 Elog entry 5 [7];
- L0 def.—amplitude > 0.3 photoelectrons;
- L1 def.—10 coincidences in two adjacent PMTs in the same optical module within 20 ns;
- water properties include attenuation (60 m at 450 nm) and scattering.

### 3. Reconstruction

Using an array of hit optical modules the Chameleon Cluster (*Mesonychoteuthis hamiltoni*) reconstruction module [8] adds reconstructed tracks to the SeaTray framework. The distribution of the difference between generated and reconstructed angle is shown in Fig. 1 with an insert giving a detailed view of the peak showing a significant tail of miss-reconstruction. The main reason for this tail of miss-reconstructed events and the width of the main peak can be explained by the presence of scattering in water combined with an attenuation length of the magnitude comparable with the scattering length and large separation of the strings.

### 4. Event selection

In order to simulate the coincidence between the surface array, located on-deck on DELTA BERENIKE, and the neutrino telescope at depth the events were selected in such a way that any track used for the sample had to enter the water at a distance  $2000 \pm 20$  m from the central axis of the detector. The scheme is illustrated in Fig. 2.

### 5. Results

Each of the selected MC events has been characterized by:

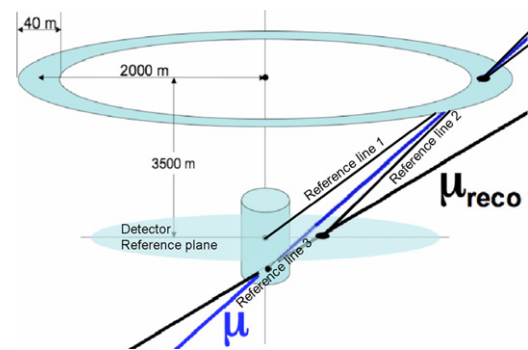
- The mean of first hit times per optical module per event. This is calculated from the earliest hit times in all the optical modules participating in the event. The time is measured from the moment when the track crosses the surface annulus.
- The number of optical modules participating in the event.
- The number of strings participating in the event.
- The angle between the reconstructed track and Reference line 1—through the center of the detector and the surface array.

- The angle between the reconstructed track and Reference line 2—through the intersect of the reconstructed track with the detector mid-plane and the surface array.
- The angle between the reconstructed track and Reference line 3—through the point of closest approach of the reconstructed track to the symmetry axis of the detector and the surface array.

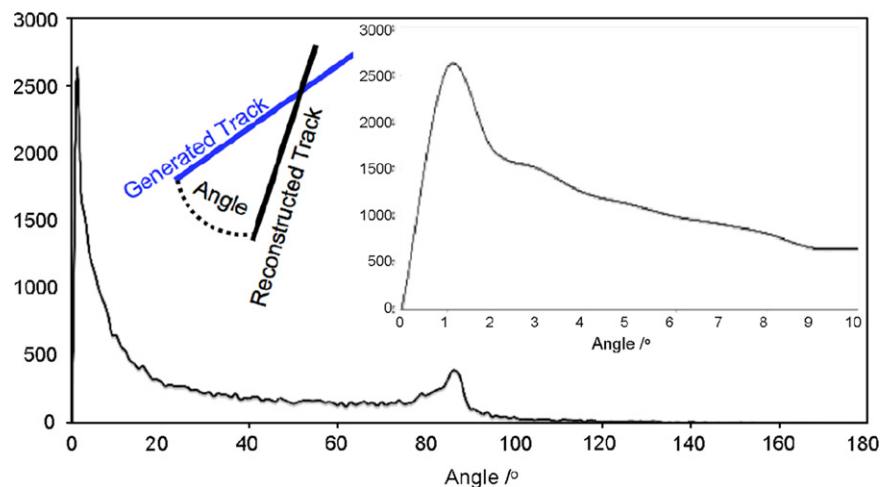
In this note we focus on Reference line 1, which was chosen as the datum as it is the one that is least susceptible to systematic error due to the reconstruction algorithm inefficiencies. Its suitability was gauged by examining the distribution of angular mismatch between the generated Monte Carlo muon track and Reference line 1. The results are shown in Fig. 3. The distribution peaks at  $0.5^\circ$  suggesting that this would be a reasonable datum for the mismatch angle analysis.

Fig. 4 shows the distribution of mean times of events. The FWHM of the distribution is  $\sim 1000$  ns, which corresponds to  $\sim 225$  m light travel in water, which is well inside the fiducial volume of the  $\text{km}^3$  size detector.

As the events are already pre-selected by demanding a coincidence between surface region and KM3NeT there is no need for a time cut. The full-uncut set is shown in Fig. 5 for the mismatched angle relative to Reference line 1. The peak at  $5^\circ$  seen in Fig. 5 is to be expected given that the full  $\text{km}^3$  size detector subtends an angle of  $\sim 9^\circ$  on the surface. There is a significant tail



**Fig. 2.** Illustration of setup for the event selection for the Ship-KM3NeT calibration simulation. The track labeled  $\mu$  indicates the Monte Carlo generated track while the  $\mu_{\text{reco}}$  track indicates the reconstructed track. The track needs to be registered in both the surface array and the neutrino telescope at depth. In order to increase the statistics the surface region was defined as an annulus of radius 2000 and width 40 m. The use of an annulus instead of the physical region of the surface ship gives an enhancement in the statistical sample of  $\sim 500$ .



**Fig. 1.** Distribution of the angle between the generated Monte Carlo muon track and the reconstructed track

and the peak is broad. This, most likely, can be ascribed to the accuracy of reconstruction.

The above analysis was conducted for the KM3NeT at a depth of 3500 m. A total of 10 files for 4500 and 5000 m each were used. For these greater depths the available sample of Monte Carlo muons does not offer a sufficient number of muons passing through the annulus of Fig. 2 and reaching the desired depth. Therefore, in order to gain a sufficient size statistical sample of those muons that pass through the surface of the sea within a circle of 8000 m from the axis of the KM3NeT were selected. This is illustrated in Fig. 6. This is different from the analysis employed for the 3500 m deep KM3NeT (compare Figs. 2–6).

The results of analyzing the mismatch angle for KM3NeT located at a depth of 4500 m are shown in Fig. 7.

### 6. Triggering scheme

In Fig. 4 the distribution of trigger times in the KM3NeT array is shown. The time is measured relative to the crossing of the sea

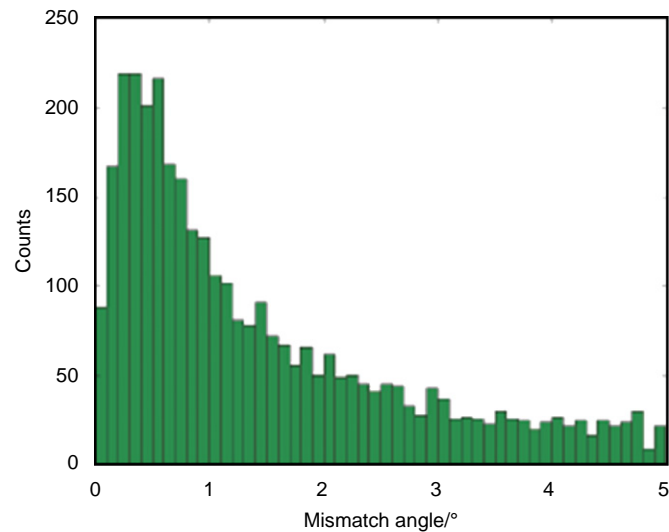


Fig. 3. Distribution of mismatched angle between the generated Monte Carlo track and Reference Line 1.

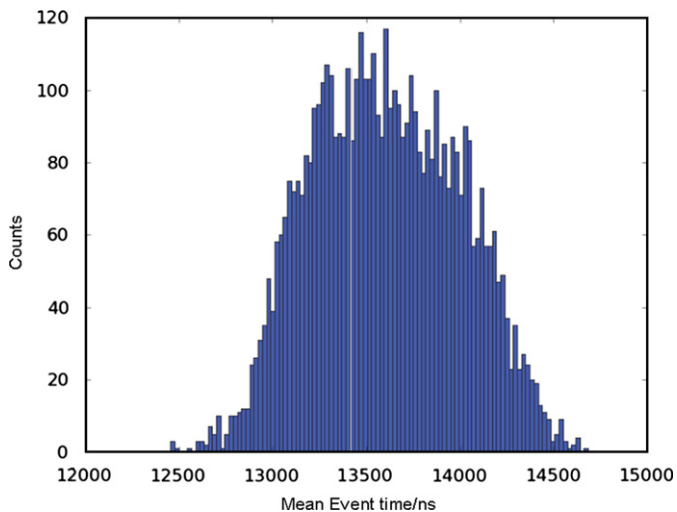


Fig. 4. Distribution of the means of first hit times per optical module per event. Zero time occurs on the surface of the water with the surface array located at 2000 m from the KM3NeT axis and KM3NeT at a depth of 3500 m.

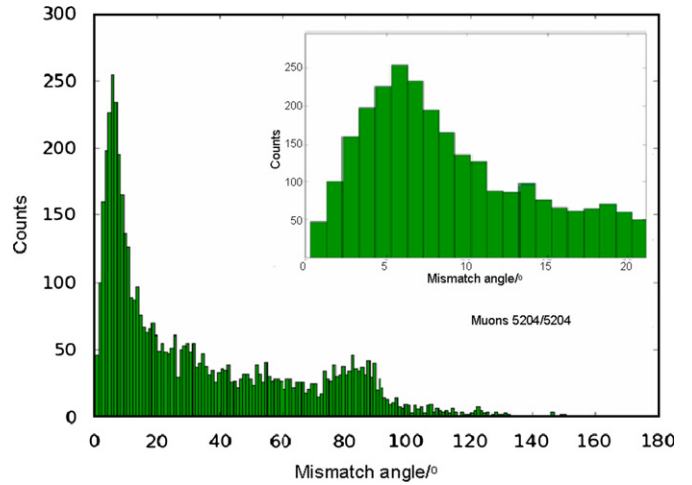


Fig. 5. Distribution of mismatched angles for the sample of muons used. The mismatch angle is measured from the reconstructed muon to the Reference Line 1, shown in Fig. 2. The bin size is 1°. The horizontal distance from the surface array and the central axis of KM3NeT is 2000 m and KM3NeT at a depth of 3500 m.

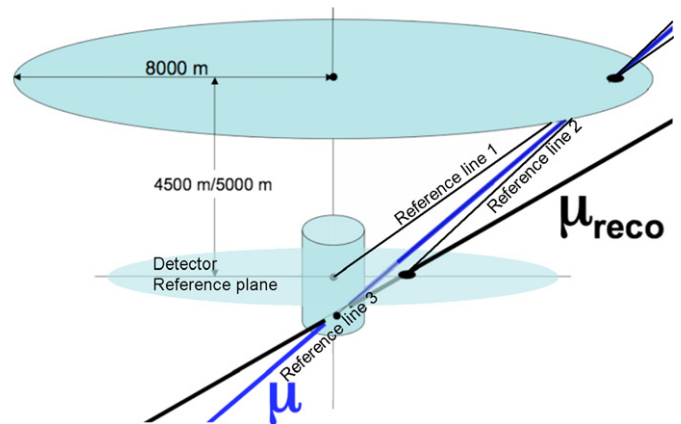


Fig. 6. Illustration of event selection setup for simulation at 4500/5000 m depth. The track labeled  $\mu$  indicates the Monte Carlo generated track while the  $\mu_{reco}$  track indicates the reconstructed track. The track needs to be registered in both the surface array and the neutrino telescope at depth.

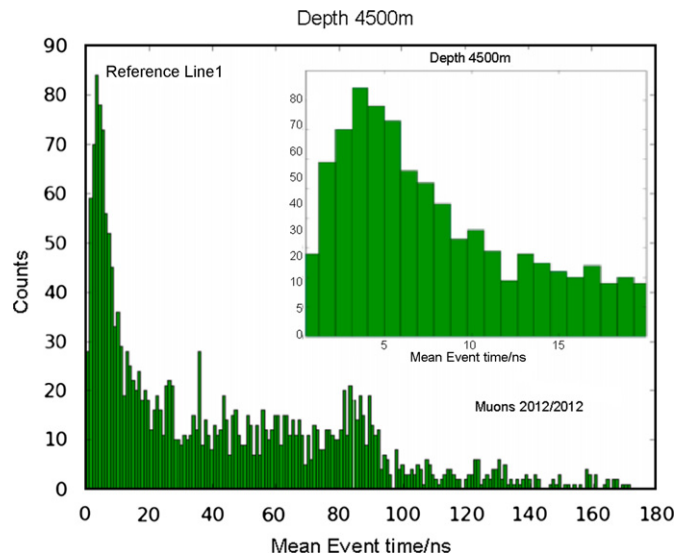


Fig. 7. Distribution of mismatched angles for the sample of muons used. The mismatch angle is measured from the reconstructed muon to the Reference Line 1, shown in Fig. 8. The bin size is 1°. KM3NeT is at a depth of 4500 m.

surface. The distribution is centered on 13,500 ns corresponding to a propagation distance of ~4 km, which is as expected for a 3.5 km deep detector with the surface array at 2 km from the central axis of the detector. The width of the distribution is ~1000 ns.

As there is no possible physical connection between the surface array and the KM3NeT array data selection must be conducted using the event clock stamp. Thus given a reconstructed event trigger in a KM3NeT data set one looks for a surface array trigger occurring at an appropriate propagation time earlier time than the KM3NeT event within a 1000 ns window.

The question still remains on how to define the surface array trigger. The canonical number for the rate of secondary particles at sea surface from cosmic ray showers is 1 particle per cm<sup>2</sup> per minute. This translates to a rate of 167 particles per m<sup>2</sup> per second. As a safety factor a 200 Hz m<sup>-2</sup> rate will be assumed henceforth.

If the entire surface of the vessel (1000 m<sup>2</sup>) is covered by a scintillator and used as a single unit then the expected background rate of the array, ignoring any contributing noise from photomultipliers, will be 200 kHz. Thus in a 1000 ns window, it would mean 0.2 random events. However, by segmenting the surface array into say 200 sections of 5 m<sup>2</sup> each, a significant reduction of the fake rate can be achieved. As the majority of the background events in the surface array will be caused by low

energy particles it can be expected that any muon energetic enough to be able to reach the KM3NeT detector will be part of an air shower. The particles of the shower front should arrive at the surface array within 150 ns of each other.

Accounting for the curvature of the shower front and particle density, there may be an additional delay. The delay, of up to ~10 ns due to the shower front curvature, is typical for a shower. For reasons of safety it is proposed to take the gate to have a 200 ns width. The maximum delay between detection by distributed scintillator modules is estimated to be about 150 ns. Therefore the expected rate of n-fold majority random coincidence for a surface array consisting of 200 sections of 5 m<sup>2</sup> each (1 kHz background plus 500 Hz photomultiplier dark noise) without including dead time in a 1000 ns window is given by the following equation

$$\mathfrak{R} = \left(\frac{N}{n}\right) n f^n \tau^{n-1} \tag{1}$$

where  $N=200$ ,  $f=1.5$  kHz, and  $\tau=200$  ns.

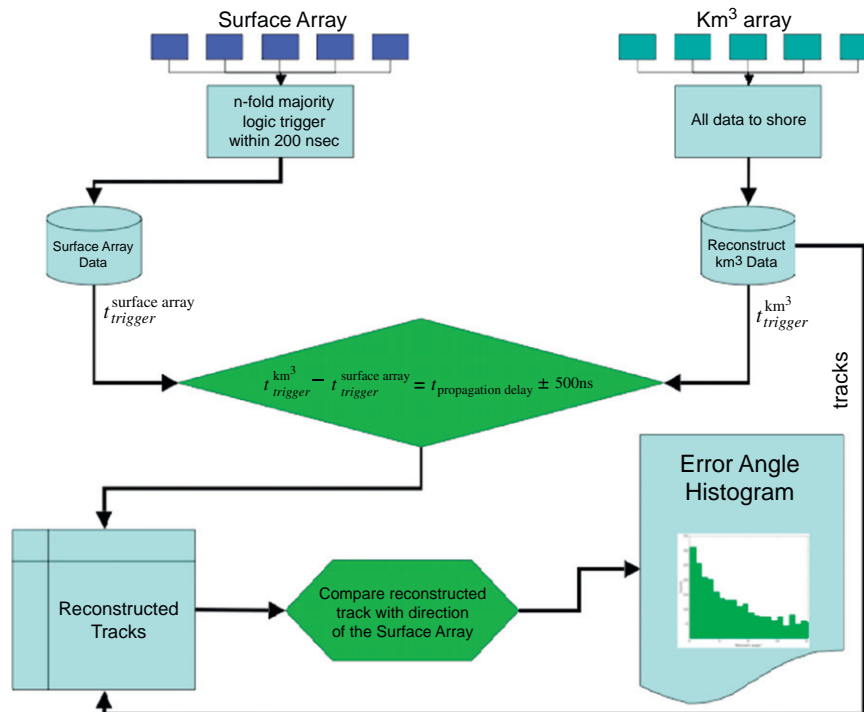
Muons energetic enough to penetrate down to the deep km<sup>3</sup> size detector can be produced only in highly energetic cosmic ray showers. At sea level charge particle content of such showers would be well in excess of 10<sup>6</sup>. Using Greisen's parameterization of muon densities at sea level [9] the expected muon density at a radius of 15 m from the shower core is around ~20 m<sup>-2</sup>. Although there will be a high degree of fluctuation in particle densities, particularly for hadronic showers, nevertheless the expected participation of the surface array modules is expected to be in excess of 10. From Table 1 it is evident that at a majority of logic participation level of 5 modules the accidental coincidence rate is extremely low.

**Table 1**  
Accidental trigger rates as a function of majority logic multiplicity expressed as a rate per second and per 1000 ns coincidence window.

n-fold majority	Random surface array rate/Hz	Random surface array—KM3NeT coincidence events in a 1000 ns window
1	300,000.0	$3.0 \times 10^{-1}$
2	17,910.0	$1.8 \times 10^{-2}$
3	531.9	$5.3 \times 10^{-4}$
4	10.5	$1.0 \times 10^{-5}$
5	0.15	$1.5 \times 10^{-7}$

**7. Methodology**

The analysis path has been summarized in a flow chart in Fig. 8. The triggering scheme for the surface array has already



**Fig. 8.** Data analysis flow chart.

been discussed above. The analysis chain would involve using the GPS trigger time of the surface array and selecting for the reconstructed tracks in the KM3NeT that occur so that their trigger time is delayed by the time necessary for a muon to reach the KM3NeT telescope. The coincidence window should be of the order of 1000 ns. For these events a direction from the surface array to the KM3NeT can then be defined on an event-by-event basis. The angular error between this direction and the reconstructed track can then be histogrammed to define the distribution of errors. This histogram gives a measure of the absolute pointing accuracy of the KM3NeT detector.

Further refinement is possible here. By recoding the times individual modules detect particles of the shower front shower direction reconstruction is possible. Reconstruction accuracy of a few degrees is readily achievable with finer segmentation of the modules to an order of  $1 \text{ m}^2$ .

## 8. Further work

The above analysis was conducted on a limited statistical sample of Monte Carlo muons. The small sample was used mainly to gain results in a reasonable time period. However, a larger sample is necessary for greater accuracy particularly for larger depth (4500 and 5000 m).

Additionally, the poor reconstruction quality of the muon tracks can be, possibly, attributed to the presence of scattering mechanism in the simulation of Čerenkov photon propagating

through deep water. For comparison and to further investigate this issue, Monte Carlo muon files propagated through scattering free water have been requested. These new files will need to be analyzed using the methodology described in this report.

## Acknowledgments

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