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Results and simulation of the prototype detection unit of KM3NeT-ARCA

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Abstract. KM3NeT-ARCA is a deep sea high energy neutrino detector. A detection unit prototype was deployed in the future KM3NeT-ARCA deep-sea site, off of the Sicilian coast. This detection unit is composed of a line of 3 digital optical modules with 31 photomultiplier tubes on each one. The prototype detection unit was operated since its deployment in May 2014 until its decommissioning in July 2015. The results of the calibration of this detection unit and its simulation are presented and discussed.

1 Introduction

KM3NeT represents the next generation of Mediterranean undersea telescope, following the technical and scientific results of the ANTARES [1] neutrino telescope and the NEMO [2] and NESTOR [3] pilot projects. The two main goals of this detector are the detection of high energy neutrinos and their sources and the determination of the neutrino mass hierarchy with the detection of low energy neutrinos. The detection of neutrinos is possible thanks to the Cherenkov light emitted by the secondary charged particles. The secondary particles are produced by weak interaction in the vicinity of the detector. KM3NeT uses 17 inch digital optical modules (DOM) containing 31 3 inches photomultiplier tubes (PMT) for a total of photocathode area of 1400 cm^2 [4]. The final line design contains 18 DOM along a rope, anchored to the seabed and maintained close to vertical with a buoy. In May 2014, a prototype detection unit (Pre-Production Model DU, PPM-DU) with 3 DOMs was installed 80 km off the Sicily [5]. This prototype implements the mechanical structure, the electro-optical power supply and communication, allowing simultaneous data taking of the three DOMs. The PMT model installed in DOM 1 and DOM 2 is the D783KFLA produced by ETEL [6], while DOM 3 contains the R12199-02 Hamamatsu PMTs [7]. The current design for KM3NeT uses the R12199-02 PMT. The PMTs are surrounded by reflector rings at an angle of 45 degrees with respect to the PMT axis, 16 mm in width for ETEL and 17 mm for the Hamamatsu PMTs [4]. Figure 1 represents the prototype line and the DOM design and its PMT arrangement.

The simulation of the KM3NeT detector is based on the same principle as ANTARES [8]. Only two elements of the simulation chain had to be upgraded: The step-by-step high precision simulation of the optical module and the *km3* simulation software, briefly described in the next section. Then in section 3 the results will be presented and discussed.

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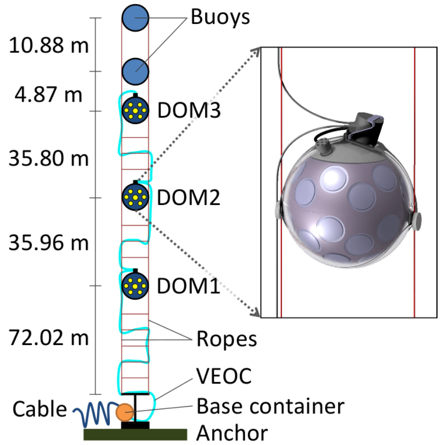

Figure 1: Schematic of the PPM-DU (not to scale). The DOMs are spaced by 36 m vertically. The buoys are made of 2 empty glass spheres. The vertical electro-optical cable (VEOC) connects the DOMs with the base. The base is connected to the submarine infrastructure, then to the shore station. The inset shows a DOM attached to the two ropes, which leaves the line free to move with the sea current.

2 The simulation

2.1 The step-by-step simulation

The step-by-step simulation is described in detail in [9, 10]. It is the very first step of the full simulation of ANTARES, NEMO and KM3NeT neutrino detectors. It manages the propagation of each photon, from their sources, through their different interactions in the matter, to the PMT photocathode. When these photons reach the photocathode, a complementary accurate calculation process is used in order to obtain a precise detection probability. This calculation takes into account the thickness and the complex index of the photocathode to provide the photoelectron production as a function of wavelength and incident angle, essential for underwater neutrino detectors. This simulation is used to produce the OM and DOM detection efficiency as a function of the angle and the wavelength of the incident photon (angular acceptance). This simulation has been validated by comparison with laboratory measurements. These measurements were done with an LED scanning of the ANTARES OMs and KM3NeT PMTs [11].

2.2 The full detector simulation

To simulate neutrino detectors, a full simulation would be far too slow. Therefore, the results of the step-by-step simulation are tabulated and used as inputs for the next simulation step, called *km3*. Thanks to this efficiency, the water properties and the number of photons produced by Cherenkov effect, the *km3* simulation is able to reproduce the full detector detection response. It is based on 4 main steps:The charged lepton directionality and energy are simulated a priori with the fast MUPAGE code [12], as a function of the water properties, to be propagated in the *km3* simulation can; the density of the Cherenkov photons production is calculated along the lepton (~100/cm); the photon probability density as a function on time is calculated along the Cherenkov front; at the position of each Optical module the probability to be detected is calculated as a function of the step-by-step simulation tabulated results. This method has been chosen for its good compromise between precision and calculation time, and is used for KM3NeT-ARCA and ORCA.

3 The prototype detection line simulation and calibration results

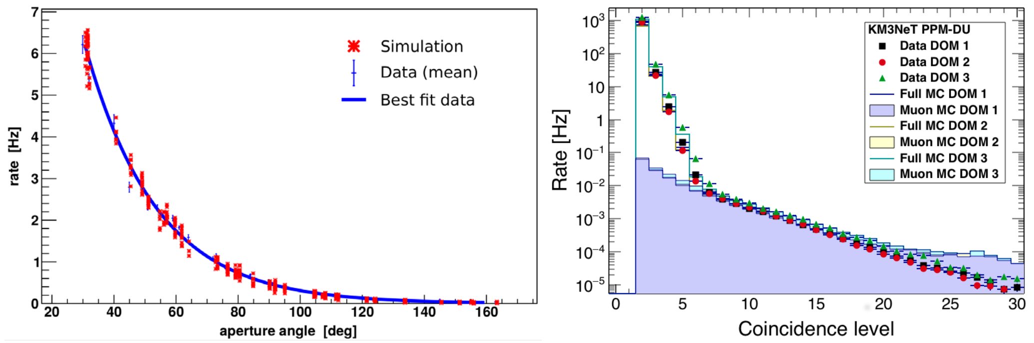

Figure 2: The upper figure shows the coincidence rates as a function to the angle separation between the pair of PMTs. The blue points represent the data from [5] (mean over multiple PMTs), the blue line represents the data best fit and the red points represent the step-by-step simulation results. The lower graphic shows the multi-fold coincidences for the data and the simulation. The step-by-step simulation is used for the ^{40}K coincidences and the global *km3* simulation is used for the muon simulation.

3.1 Intra-DOM calibration

Natural ^{40}K radioactive decays in sea water produce up to 150 Cherenkov photons. A decay close to the DOMs can be detected by one or multiple PMTs (single or multi-fold). Beyond the background it may represent, it's a calibration source for intra-DOM time offsets between the PMTs and their intrinsic transit time spread. The measured mean time spread of PMTs is 5 ns (FWHM). In addition, knowing precisely the water salinity [13], the coincidence rate can be used for the efficiency adjustment of the simulation. The two-fold coincidence rate is shown in Figure 2 as a function of the angular separation between pairs of PMTs in the DOM 3. The angular dependence has been fitted to an exponential function. The step-by-step simulation results are represented at their best fit, and show a good accordance between the measured rates and the simulation for all angles between the PMTs of the DOM.

3.2 The inter-DOM calibration

A LED nanobeacon system operating on the lowest DOM has been used to calculate the inter-DOM time offsets. The distribution of time differences, taking in account the travel time in water, of hits in coincidence with the LED emission time has been fitted with a Gaussian function. The resulting mean time offsets of DOMs 2 and 3 with respect to DOM 1 are, respectively, approximately 230 ns and 380 ns. Leaps of about ten ns have been observed, and are due to power cycles of the corresponding module in the shore station. Otherwise no time offset shifts were observed within a few nanoseconds. In addition, thanks to its multi-DOM configuration, the prototype line was able to detect down-going muons. The signal from muons has been used to cross check the inter-DOM calibration by a χ^2 minimization algorithm applied to the data and the simulation. Figure 2 illustrate the agreement of simulation and data. This latest measurement was in agreement within 2 ns with the LED beacon calibration, and shows a good agreement with the full detector simulation *km3*.

Conclusion

The prototype project of the PPM-DU validated the KM3NeT structure at the depth of 3500 m, provided a test bench for the data taking and analysis and showed a reliable calibration procedure for the detection efficiency and the time offsets between PMTs and between DOMs. The simulation showed a good understanding of the detector, from the DOM with the step-by-step simulation to its line configuration with the *km3* full detector simulation. It provided the perspectives on the future KM3NeT-ORCA detector in this site, which is currently in the deployment stage.

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