Study of the calibration potential of HELYCON detectors with ANTARES

Jean-Pierre Ernenwein [a,*] Apostolos Tsirigotis [b,**] Spyros Tzamarias [b,**]

[a] *Université de Haute Alsace, 61 rue Albert Camus, F68100 Mulhouse, France*

[b] *School of Science and Technology, Hellenic Open University, Tsamadou 13-15 & Aghiou Andrea, Patras 26222, Greece*

Abstract

The "HEllenic LYceum Cosmic Observatories Network" (HELYCON) collaboration is constructing a network of detector stations dedicated to the study of Extensive Air Showers. The use of HELYCON detectors is also envisaged for the calibration of a cubic kilometer scale Mediterranean neutrino telescope by means of an array of these detectors at the sea surface. The ANTARES framework is well-suited to perform a first test of the principle: a feasibility study is ongoing and a test in real conditions is foreseen. In this paper the requirements for evaluating the calibration potential of a surface array in the ANTARES context are discussed.

Key words: ANTARES, calibration, surface array
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1. Introduction

Since June 2008 the ANTARES detector is complete, gathering 12 lines equipped with a total of 885 Photomultiplier Tubes (PMT). The apparatus is located in the Mediterranean Sea, at a depth of 2475 m, 40 km off Toulon [1]. The detection of the Cherenkov light emitted along muons tracks enables ANTARES to reconstruct the trajectory of these particles. In case of muons produced by upgoing neutrinos the expected good angular resolution of ANTARES will allow neutrino astronomy. The ANTARES lines are kept vertical by means of a dead weight at their bottom and a buoy at their top [2]. A positioning system combining compasses, tiltmeters and acoustic measurements allows to determine the position of the Optical Modules with a precision of 10 cm (0.5 ns). Dedicated electronics for the readout of the PMTs and the good optical properties of the sea water lead to a global time resolution of 2 ns in the measurement of the Cherenkov photon arrival time. Several methods are used to perform the monitoring and the calibration of the time and the charge: LASER and LED flashers [3], ^{40}K decay induced Cerenkov light, measurement of the single photoelectron peak and of the pedestals.

The angular resolution for up-going neutrinos is expected to be 0.3° for $E_\nu > 10$ TeV. As a neutrino telescope cannot use standard candels to test its absolute pointing, the absolute zenith given by ANTARES will be inferred from the knowledge of the position of all its parts.

In this paper we discuss the possibility to perform an independant measurement of the absolute direction given by the telescope, using an array of scintillators floating at the sea surface and positioned with GPS. This idea was previously developped in the

* ANTARES
** HELYCON
Email address: `ernenwein@cppm.in2p3.fr, Tel: +33491827691, Fax: +33491827299` (Jean-Pierre Ernenwein).

KM3NeT framework [4][5]. ANTARES is well suited to test the potential of this method. Using Monte Carlo simulations, we will show how the surface array measurements could constrain the absolute zenith angle measured for down-going events initiated by high energy cosmic primaries.

2. HELYCON detectors and KM3NeT calibration

The HELYCON: HEllenic LYceum Cosmic Observatories Network [5], collaboration is constructing an Extensive Air Shower (EAS) detector array consisting of several detector stations distributed over extended geographical areas in Western Greece and surrounding islands. Each station is equipped with three or four large plastic scintillation counters providing each an effective area of 1 m^2. Each station also includes a Global Positioning System (GPS) device, trigger and digitization electronics, slow control electronics and a computer based data acquisition system. The stations will be mounted on the roofs of high-school and university buildings whilst the time synchronization between the detector stations will rely on the GPS time. The main goal of the project is to contribute to the study of time and directional correlations between cosmic ray activities over large distances.

In addition, a floating array of HELYCON detectors could be used as a sea-top calibration infrastructure for a deep sea neutrino telescope, like the one under design by the KM3NeT consortium. Indeed, at least 35% of the cosmic showers initiated by primaries in the energy range 100 TeV-5 PeV contain energetic muons able to penetrate 2500 m to 4000 m of sea water. The comparison of the muon track reconstructed by the telescope with the direction and the impact of the shower axis reconstructed by the surface array can be used in order to reveal systematic angular errors in the determination of the track parameters by the neutrino telescope and provide an absolute positioning of the undersea detector.

3. ANTARES implementation

A first test of HELYCON detectors used as a sea-top calibration infrastructure could be performed in the ANTARES framework. Since June 2008, ANTARES is complete with 12 lines. A reduced setup of HELYCON detectors located on a platform dragged by a boat, or on the boat itself, could be tested to evaluate

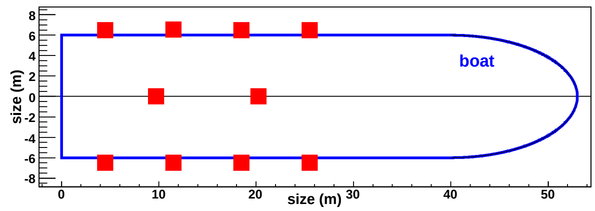

Fig. 1. One of the 4 surface array setups tested using Monte Carlo Simulations: on each side of the boat 4 scintillators are fixed, the 2 last scintillators being located on the deck

the rate of events detected by both ANTARES and the surface array. The comparison event by event will then give an estimate of the possible systematic angular errors.

We have performed Monte Carlo simulations to study the potential of 4 surface array setups: one of them is shown figure 1. Two locations are tested for each of these 4 setups: just above the ANTARES detector and 1 km away from the centre of the detector.

The steps of the simulation are the following:

1 Simulation with CORSIKA [6] of atmospheric showers initiated by protons of energy ranging between 100 TeV and 5 PeV,
2 Simulation of the surface array measurements and reconstruction of the shower axis,
3 Propagation of the muons towards the ANTARES detector,
4 Simulation of the detection by ANTARES and reconstruction of a track [7], assuming an optical background of 60 kHz per OM,
5 Event by event comparison to study the difference between the track parameters and the surface array measurements.

The different setups which have been simulated contain 9 to 16 scintillators, with a maximal lever arm of 20 to 30 meters. The intrinsic time resolution for one scintillator is 2 ns if we require an energy deposit greater than 4 MIPS. The resulting resolution on the zenith angle of the shower axis is 3°RMS in the studied setups.

The counting rate of a single scintillator has been measured in the laboratory and reaches 1.5 Hz. When we require 3 scintillators in order to be able to perform the shower axis reconstruction, the event rate is expected to be of the order of 3 per minute.

The performed simulations cover 5 days of atmospheric showers: in the following lines we consider a sea campaign of 5 days, and we give the results which could be achieved in such a campaign.

Figure 2 shows an event by event comparison between the zenith angle θ of the track reconstructed in ANTARES and the zenith angle measured by the surface array, for the setup of 10 scintillators displayed in figure 1. The two histograms shown on the figure represent the two tested locations for the surface array: just above the detector and at a distance of 1 km, which corresponds to $\theta = 24°$. The Root Mean Square (RMS) of the distributions are rather equivalent, while the rate of events is reduced in case of $\theta = 24°$, because of the larger amount of traversed matter.

In the distribution of $\Delta\theta$ the main error contribution origins from the surface array measurement. Indeed, in this distribution, quality criteria have been applied on the reconstructed track in ANTARES, leading to an estimated resolution of about 1.5°RMS ($\sigma \simeq 1°$ for a Gaussian fit) [1], which is better than the 3°RMS ($\sigma \simeq 2°$ for a Gaussian fit) reachable with the studied surface array setups.

For looser quality requirement on the reconstructed track in ANTARES, the resolution for down-going events degrades to 4°RMS ($\sigma \simeq 2°$ for a Gaussian fit): for this case, an event by event comparison is displayed in figure 3. The error on the mean value [2] is given by $RMS/\sqrt{N}$, N being the accumulated number of events during the sea campaign duration, i.e. 5 days. In both cases (tight or loose quality cuts: figures 2 and 3) the error on the mean value is 0.4° for a surface array located above ANTARES and 0.5° for a surface array placed at 1 km from the centre of ANTARES [3]. We can then infer that the surface array is able to give a constraint better than 0.5° on the possible systematic offset of the zenith angle measured by ANTARES. However, due to the primary cosmic ray flux uncertainties and shower reconstruction efficiency uncertainties there is a systematic error to the expected rates of about 30%. This results in a 15% systematic error to the constraint.

We can remark also that in case of high quality criteria on the reconstructed track, the surface array cannot be used to measure precisely the ANTARES resolution, its own resolution being not good enough. However, the surface array may be a simple way to check the resolution if quality cuts are relaxed.

On the other hand, the resolution of ANTARES on the azimuth angle ϕ of the studied down-going events reaches, at $\theta \sim 24°$, 12°RMS ($\sigma \simeq 4.5°$ for a Gaussian fit) with loose quality cuts and 7°RMS ($\sigma \simeq 3°$ for a Gaussian fit) with tight quality cuts. The resolution of the surface array on ϕ reaches 6°RMS ($\sigma \simeq 3°$ for a Gaussian fit). The event by event comparison between the azimuth angles measured by the surface array and ANTARES will enable to set a constraint of 1.5° for a systematic error on the azimuth angle ($RMS/\sqrt{N}$, 5 days).

Moreover, the surface array will allow the estimate of the ANTARES resolution in ϕ.

4. Coincidences between events

The previous study assumes that we are able to match ANTARES and surface array events with a negligible rate of fortuitous coincidences. This is achieved thanks to the combination of time and direction informations.

The surface array is an independant and autonomous apparatus storing events on a hard drive at a frequency of the order of 3 per minute, and time-stamping these events with a precision better than 1 μs (GPS).

On its side, the ANTARES experiment stores events at a frequency of 10 Hz, and attributes a global GPS time to the events with a precision of about 100 μs.

[1] These numbers are computed using a full simulation of ANTARES for the down-going events common with the surface array. These events differ from the usual case of up-going events. Indeed the energy of the muons is of the order of 100 GeV, while the above mentionned number of 0.3° (median of space angle) is for $E_\nu > 10$ TeV. Moreover, the ANTARES detector −and the current reconstruction− are optimized for up-going single muons, yielding a weak angular resolution for down-going multiple muons.

[2] For Gaussian distribution, the formula is the statistical 1σ estimator for the error on the mean value, it agrees with the error on the mean given by a Gaussian fit.

[3] On some distributions, we can observe a shift of the mean with respect to the value 0: this shift can reach 3 times the error on the mean for simulations with a surface array at the top of ANTARES. A contribution to this offset is due to the asymmetry of θ values ($\theta \geq 0$), which results in an asymmetry in the $\Delta\theta$ distribution at low θ. Another contribution origins from the quality of the reconstruction: work is on-going to improve both ANTARES and HELYCON reconstructions.

Without direction information, the contamination by fortuitous coincidences would be of the order of one event per day. But if we use the directional information, this rate falls drastically with the solid angle cut, to become negligible in a cone of a few degrees.

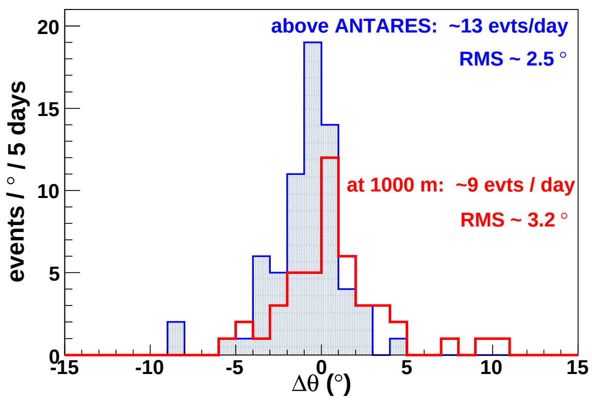

Fig. 2. Zenith angle event by event comparison between surface array shower axis measurement and reconstructed track in ANTARES, with quality cut. The difference of rates is mainly due to the muon absorption which is greater for zenith around 24° than for pure down-going muons

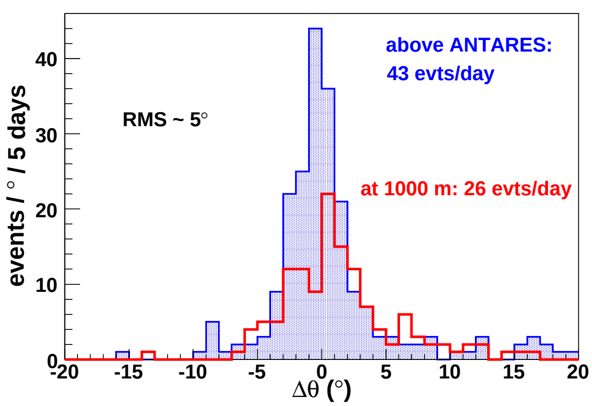

Fig. 3. Zenith angle event by event comparison between surface array shower axis measurement and reconstructed track in ANTARES, with loose quality cut. The difference of rates is mainly due to the muon absorption which is greater for zenith around 24° than for pure down-going muons. The RMS of the 2 distributions are similar, both being slightly better than the value of 5° indicated on the figure.

5. Conclusion and perspectives

In this work we have estimated the potential of a floating surface array in the calibration of an underwater neutrino telescope of the size of ANTARES. Using Monte Carlo simulations (CORSIKA, HELYCON software and ANTARES software), we can conclude that a 5 days sea campaign with a surface array made of 10 scintillators distributed on an area of 13×23 m^2 would be useful to reveal a systematic error of about 0.5° on the zenith angle reconstructed by the telescope. This constraint becomes 1.5° for the azimuth.

In the current simulations only protons have been simulated. Simulations including heavier nuclei are on-going. The very preliminary results lead to an increase of event rates and a resulting improvement of the angle offset measurements. Besides, new developments are in progress concerning the extensive air shower and muon track reconstruction, constituting another way to improve the event rate and consequently the performance of the method.

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