Common Simulation Tools for Large Volume Neutrino Detectors

A. Margiotta for the ANTARES Collaboration

Dipartimento di Fisica dell'Università and Sezione INFN - Bologna, viale C. Berti Pichat, 6/2, 40127 Bologna, Italy

---

Abstract

A general discussion of the organization of the Monte Carlo (MC) simulation in a Cherenkov neutrino telescope is presented. Some practical examples are taken from the simulation chain used for the ANTARES and the IceCube detectors.

Keywords:

---

1. Introduction

The goal of a neutrino telescope is the detection of astrophysical high-energy neutrinos. Actually, most of the detectable Cherenkov light is due to the passage of high-energy atmospheric muons and of muons induced by atmospheric neutrino interactions in the vicinity of the detector.

These signals represent a background for most analyses searching for astrophysical neutrinos. Indeed atmospheric muons and neutrinos are an interesting subject themselves as they can provide useful information on some features of the cosmic ray flux, like anisotropy and primary nuclei composition. In addition they are a helpful tool to calibrate the detector, to evaluate its pointing capability and its absolute positioning.

A reliable simulation allows the definition of selection criteria to reject the background and to identify interesting events, an evaluation of the sensitivity of the detector to an astrophysical neutrino flux and a check of telescope performance.

The MC simulation chain for a neutrino telescope can be divided into 3 steps:

Preprint submitted to Nuclear Instruments and Methods in Physics Research Section A April 10, 2012

- physics event generation,
- Cherenkov light emission and propagation,
- detector response.

Each step requires dedicated software packages and additional information on the characteristics of the detector, the properties of the medium (water or ice) and the acquisition conditions.

2. Physics generators

2.1. Atmospheric muons

High energy muons (E $>$ few hundred GeV) are residuals of showers produced by cosmic-ray interactions with atmospheric nuclei.

Two different strategies are possible for the simulation of the underwater/ice atmospheric muon flux :

- Full simulation of atmospheric showers + propagation of the high energy muons from the sea level to the detector active volume, underwater or under ice. In ANTARES and in IceCube, the generation of the air showers is done using the CORSIKA package [1] according to a predefined energy spectrum (γ = -2 in ANTARES) on a wide energy range (for ANTARES between 1 TeV/nucleon and 100 PeV/nucleon). The primary composition can be decided by the user at the end of the simulation chain, weighting the simulated events to a different spectrum. The CORSIKA package allows a choice between several hadronic interaction models. In ANTARES the hadronic interactions are described by the QGSJET model [2], while IceCube uses the SYBILL [3] model.
  In ANTARES the primary model composition described in [4] is used. A plot with the zenith angle distribution of data and MC is shown in fig. 1. IceCube have adopted the polygonato model described in [5]. A difference of around 25-30 % in the total flux of atmospheric muons is expected,

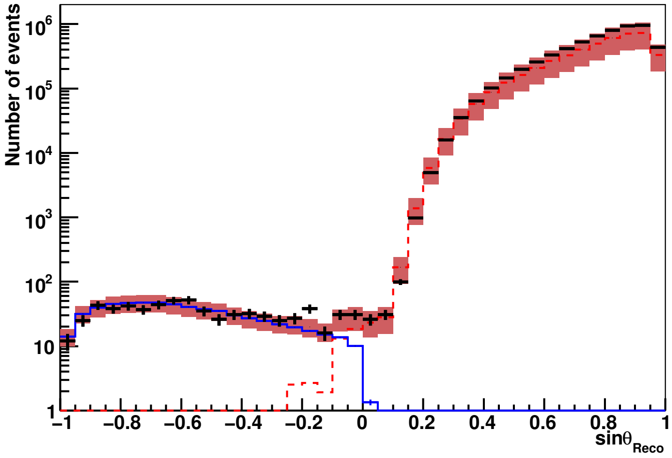

Figure 1: Angular distribution of the reconstructed tracks in the ANTARES detector. Black crosses are data collected during 2007-2010. Red line is the MC expectation provided by CORSIKA modelled according to the NSU primary composition, [4]. The shadow band indicates the systematic uncertainties due to errors on input parameters to the simulation. The blue line is the simulated atmospheric neutrino flux, see Sec. 2.2

depending on the hadronic model/ composition model combination. The muons are propagated through water with the MUSIC [6] package and through ice with MMC [7]. Both codes take into account all relevant energy-loss processes for muons passing through matter up to the highest energies.

- Parameterized description of the muon flux: in ANTARES, a code has been developed, MUPAGE, [8], which, starting from a set of formulas, is able to represent the atmospheric muon flux at different water depths. It takes into account the simultaneous arrival of muons and their energy distribution inside a bundle. The lack of flexibility in the choice of the primary composition model is compensated for by the advantage of a very quick simulation. MUPAGE has played a crucial role in the simulations for the Technical Design Report of the KM3NeT consortium [9], thanks to its low requirement in terms of CPU time.

Whichever strategy is used, all muons are stored on the surface of the active volume of the detector which surrounds the instrumented volume and whose extension is defined by the light transmission properties of the medium.

2.2. Neutrinos

- To simulate neutrino interactions in the surroundings of the detector, the package GENHEN is used in ANTARES. All neutrino flavors and both interaction channels are considered. The CTEQ6 [10] structure function with NLO corrections are used to simulate the deep inelastic scattering mechanism (DIS). At energy below 100 GeV also quasi-elastic and resonant reactions are treated with RSQ [11], which has been integrated into GENHEN. An $E^{-1.4}$ spectrum for neutrino energy is considered and later reweighted according to different flux models. The weight takes into account also the interaction cross section and the survival probability of the neutrino through Earth.

- For high-energy neutrino events, the IceCube experiment uses a code based on the ANIS [12] package, developed for AMANDA. It treats all neutrino flavors and interaction channels, simulating only the DIS mechanism. For atmospheric neutrinos, up to 300 GeV, the GENIE code [13] is used.

The atmospheric and the neutrino-induced muons in charged-current interactions outside the active volume are propagated using the MMC code in IceCube and MUSIC in ANTARES. The secondary particles in the neutral and charged current contained events are propagated with a dedicated CascadeMC code in IceCube and in ANTARES with GEANT3 [14], which performs also the production and propagation of Cherenkov photons, neglecting diffusion processes.

3. Cherenkov light emission and propagation

The Cherenkov photons emitted by the particles are propagated from the track to the optical modules (OMs), during the transport of charged particles through the active medium of the telescope. Two different methods are used for photon propagation.

The first one makes use of scattering tables for photons emitted by muons and by electromagnetic showers.

In the ANTARES simulation chain (KM3 package [15]), photons produced by the passage of muons are created starting from 1 m-long muon-track pieces (and from electromagnetic showers) within a large water volume. A model for absorption and scattering of light in water is provided as input. Individual photons are created and tracked in the water until they are absorbed or leave the volume. When a photon crosses one of several concentric spheres around its emission point, its position, time and direction are stored. The result of the convolution of these photon fields with different possible orientations of the OMs is a set of scattering tables that are used to evaluate the hit probability for all OMs during each tracking step, performed with the MUSIC code. Highly energetic radiative processes are handled by MUSIC and the corresponding Cherenkov light production is provided by the electromagnetic-shower photon tables.

In IceCube, a similar approach is done with the code PHOTONICS [16], which takes into account a full description of the ice layers.

A second method for propagating Cherenkov photons uses individual photon tracking with the Photon Propagation Code (PPC) in IceCube. It is very demanding for the CPU time. The latest version of the code makes use of Graphics Processing Units (GPUs) that allows a significant improvement in computation speed. Individual photon tracking allows for a more complete description of photon propagation in the Antarctic ice and avoids many of the approximations that are made with a numerically-tabulated propagation strategy. More details can be found in D. Chirkin's contribution at this workshop.

The same strategy has been tested in the ANTARES simulation chain (clsim code). A first comparison between the performances of the scattering table approach and the full photon tracking strategy in ANTARES does not show any significant differences. In fig. 2 the fit quality parameter for reconstructed tracks is shown. The red line refers to the MC expectations obtained with the scattering table code KM3, the blue line to the individual photon propagation

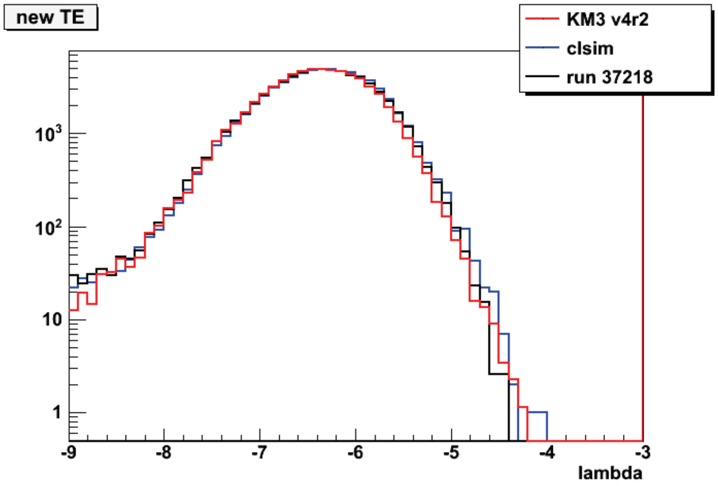

Figure 2: Distribution of the reconstruction fit quality parameter. The red line refers to the scattering table code KM3, the blue line to the individual photon propagation strategy (clsim code), the black line to data.

strategy (clsim code), the black line to data.

4. Simulation of the detector response

The last step of the chain is the simulation of the detector response. Dedicated packages describing the characteristics and the performances of the OMs and of the electronic circuits have been created according to the specific characteristics of the telescopes. In this phase the component of the signal due to the background (BG) and electronic and environmental noise must be added to the

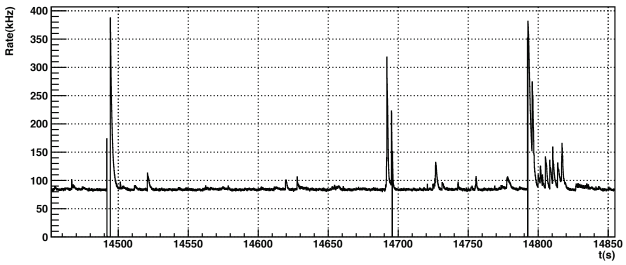

Figure 3: Counting rate registered by an ANTARES OM.

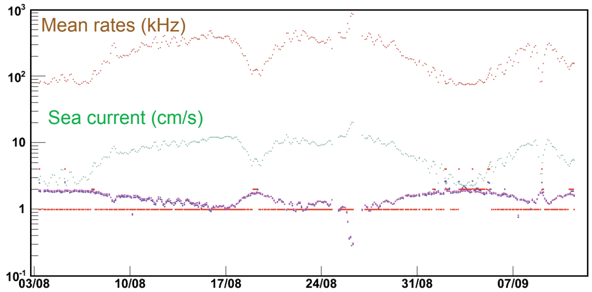

Figure 4: Mean rate (brown points) registered by the ANTARES detector between March 2008 and August 2009, compared to the reconstructed track rate, magenta points. A significant correlation is evident.

events. In IceCube the BG is almost constant, around 1 kHz, and dominated by the electronic noise with small contributions from the environment. On the contrary, in ANTARES the main contribution comes from the environment. This results in a high variability affecting significantly reconstruction algorithm performances. A strategy has been developed which allows following the time variation of the background. See the description of the Run-By-Run simulation in the next section.

Finally, the active trigger algorithms are applied to the simulated data stream in order to select potentially interesting events that will be processed with the same analysis chain used for real data.

5. RUN-BY-RUN (RBR) simulation

Fig. 3 shows a typical counting rate registered by an OM of the ANTARES detector during a few minutes of data taking. It is characterized by a minimum constant rate, the so called baseline rate, originating from ^{40}K decay and bioluminescent bacteria. Superimposed to the baseline there are occasional bursts, lasting a few seconds, associated with luminous emission by macro-organisms. Variations are registered also on seasonal time scales due to huge phenomena, like deep water formation, sea currents, passage of eddies etc., see for example

[17], as shown in fig. 4. Optical background variations have a significant effect on the reconstructed track rate and on the quality of the reconstruction fit. In addition, it affects also the number of active OMs and, consequently, the effective detector configuration. Finally, different triggers are applied depending on the environmental conditions.

The RBR strategy meets the need of simulating the time evolution of data acquisition. The basic idea is to have one Monte Carlo run for each data run.

How does it work?

A file containing a number of showers corresponding to 20-30% of the considered data-run livetime is created with MUPAGE and CORSIKA. For (anti)neutrinos a fixed number of $5 \cdot 10^8$ interactions per run are generated with GENHEN. Events are processed through the usual simulation chain. The main point is that information on the counting rate and active OMs are taken from time slices of the considered data run randomly extracted, instead of adding an average BG. The charge and the arrival time for each hit are extracted from the measured distributions, see fig. 5. Information on PMT effective threshold voltage, calibration and active trigger algorithms are read in the database and used to process the events created so far.

The main drawback is represented by a significant CPU-time requirement, which is largely compensated by several advantages: punctual representation of the optical BG (baseline and burst fraction), easy checking of the time evolution of data taking, moderate storage requirements, and simplicity of use for any analyses.

A first version of the RBR simulation has been made available in May 2011. It includes the simulation of neutrinos and of atmospheric muons with MUPAGE for the period 2007 - May 2011.

Fig. 6 shows the ratio between the reconstructed track rate in data and in RBR-MC (2-week average) for neutrinos. In fig. 7 the same ratio is for atmospheric muons (MUPAGE is used for simulation). The slope of the ratio in the latter plot is the result of using a constant value for voltage thresholds in PMT simulation. In real conditions a slow decrease is measured, which requires a periodic

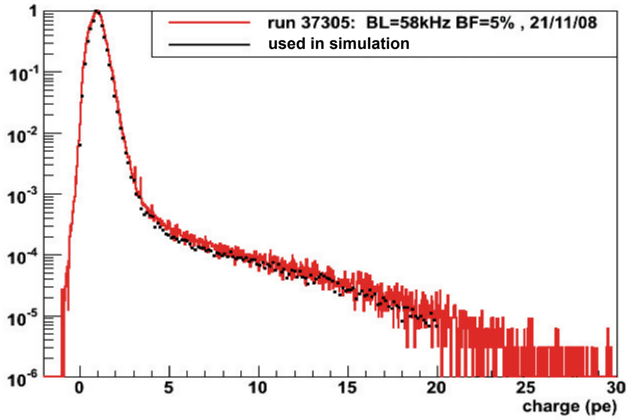

Figure 5: Distribution of the hit charge as measured in ANTARES (red points). The black points represent the values used in simulation. Presently the dynamic range is extended beyond 20 pe (not shown in the plot).

adjustment. This feature suggests using the RBR strategy to check the correct functioning of the detector.

A new version of the RBR simulation is under preparation and will be ready in a few weeks.

Thresholds and calibration taken from the database are being used for the PMT simulation. In addition, the CORSIKA simulation of atmospheric muons will be included. While for neutrinos and MUPAGE muons no intermediate files are stored, a CORSIKA file repository containing sea level sampling of atmospheric muons is being created for getting around the large CPU time requirements for shower production.

6. Conclusions

The general scheme of the Monte Carlo simulation chain used for a neutrino telescope is presented. Several examples of applications are given starting from the ANTARES and the IceCube experience.

More details on the software packages used can be found in several PhD theses available on the two collaboration web sites, [18].

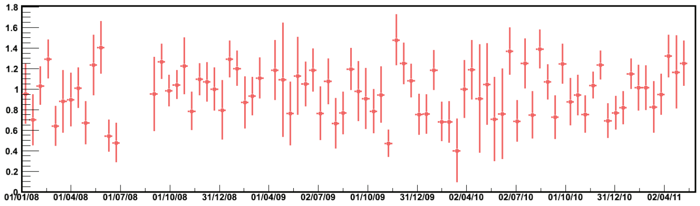

Figure 6: Ratio between the reconstructed track rate for atmospheric neutrinos in data and in MC-RBR simulation, averaged on a 2-week period.

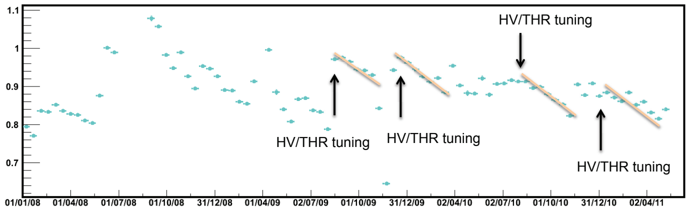

Figure 7: Ratio between the reconstructed track rate for atmospheric muons in data and in MC-RBR simulation (MUPAGE), averaged on a 2-week period. The periodic high-voltage tuning is indicated with an arrow.

Several contacts dedicated to the creation of ANTARES - IceCube working groups have been active and a common effort for the development and improvement of MC software tools is encouraged.

[1] D. Heck *et al.*, Report FZKA 6019 (1998), Forschungszentrum Karlsruhe; D. Heck and J. Knapp, Report FZKA 6097 (1998), Forschungszentrum Karlsruhe; http://www-ik3.fzk.de/~heck/corsika/physics_description/corsika_phys.html.

[2] N.N. Kalmykov, S.S. Ostapchenko, Yad. Fiz. 56 (1993) 105; Phys. At. Nucl. 56 N3 (1993) 346.

[3] R.S. Fletcher, T.K. Gaisser, P. Lipari, and T. Stanev, Phys. Rev. D50 (1994) 5710; J. Engel, T.K. Gaisser, P. Lipari, and T. Stanev, Phys. Rev. D46 (1992) 5013.

[4] S.I. Nikol'sky *et al.*, Sov. Phys. JETP 60 (1984) 10.

[5] J. Hörandel, Astropart. Phys. 19 (2003) 193.

[6] P. Antonioli *et al.*, Astropart. Phys. 7 (1997) 357.

[7] D. Chirkin and W. Rhode. Propagating leptons through matter with muon monte carlo (mmc). arXiv:hep-ph/0407075v2.

[8] Y. Becherini *et al.*, Astropart. Phys. 25 (2006) 1; G. Carminati *et al.*, Comput. Phys. Commun. 179 (2008) 915.

[9] http://www.km3net.org/

[10] H. L. Lai *et al.*, CTEQ, Phys. Rev. D 51 (1995) 4763, arXiv:hep-ph/9410404.

[11] G. D. Barr, PhD thesis, University of Oxford, United Kingdom (1987).

[12] A. Gazizov and M.Kowalski. High energy neutrino generator for neutrino telescopes. 2003. Proceedings of the 28th International Cosmic Ray Conference, Tsukuba, Japan.

[13] C.Andreopoulos, *et al.*, Nucl. Instrum. Meth. A614 (2010) 87.

[14] http://wwwasd.web.cern.ch/wwwasd/geant/index.html

[15] D. J. L. Bailey. PhD thesis, Wolfson College, Oxford, UK, 2002.

[16] J. Lundberg et *et al.*, Nucl.Instrum.Meth. A581 (2007) 619.

[17] H. van Haren *et al.*, Deep-Sea Research I 58 (2011) 875.

[18] http://antares.in2p3.fr/, http://icecube.wisc.edu/.