

Atmospheric MUons from PArametric formulas: a fast GEnerator for neutrino telescopes (MUPAGE)

M. Bazzotti*, S. Biagi*[†], G. Carminati*[†], S. Cecchini*[‡],
T. Chiarusi[†], A. Margiotta*[†], M. Sioli*[†] and M. Spurio*[†]

*Dipartimento di Fisica dell'Università di Bologna, Viale Berti Pichat 6/2, 40127 Bologna, Italy

[†] INFN, Sezione di Bologna, Viale Berti Pichat 6/2, 40127 Bologna, Italy

[‡] INAF-IASF, Via Gobetti 101, 40129 Bologna, Italy

Abstract. Neutrino telescopes are opening new opportunities in observational high energy astrophysics. In these detectors, atmospheric muons from primary cosmic ray interactions in the atmosphere play an important role. They provide the most abundant source of events for calibration and for testing the reconstruction algorithms. On the other hand, they represent the major background source.

The simulation of a statistically significant number of muons in cubic kilometer neutrino telescopes requires a big effort in terms of computing time. Some parameterizations are currently available, but they do not take into account the arrival of muons in bundles. A fast Monte Carlo generator (MUPAGE) was developed to generate single and multiple atmospheric muon events in underwater/ice neutrino telescopes. The code reduces the computing time for the simulation of atmospheric muons significantly.

The event kinematics is produced on the surface of a user-defined cylinder, virtually surrounding the detector volume. The flux of muon bundles at different depths and zenith angles, the lateral spread and the energy spectrum of the muons in the bundles are based on parametric formulas [1], [2]. These formulas were obtained according to a specific primary cosmic ray flux model and constrained by the measurements of the muon flux in the MACRO underground experiment [3].

Some examples of MUPAGE application are presented.

Keywords: Simulation of atmospheric muons, neutrino telescopes, Monte Carlo generator

I. INTRODUCTION

The most abundant signals for a neutrino telescope are due to high energy muons resulting from the extensive air showers produced by interactions between primary cosmic rays (CRs) and atmospheric nuclei. Although neutrino telescopes are located at large depths under water or in ice, taking advantage of the shielding effect offered by these detector media, a large flux of high energy atmospheric muons can reach the active volume of the detectors.

The atmospheric muons represent an insidious background for track reconstruction as their Cherenkov light

can mimic fake upward going tracks. This kind of signatures can be confused with the cosmic neutrino signals that neutrino telescopes are searching for. On the other hand, atmospheric muons are a useful tool to test offline analysis software, to check the understanding of the detector and to estimate systematic uncertainties. Moreover, the pointing capability of the telescopes can be studied using atmospheric muons through the measurement of the moon shadow.

Atmospheric muon bundles can be accurately reproduced by a full Monte Carlo (MC) simulation (e.g. CORSIKA [4]), starting from primary CR interactions with atmospheric nuclei, generating the resulting large number of air showers and propagating the muons through sea water or ice. A full MC requires a large amount of computing time and therefore the production of a large statistical event sample cannot be easily obtained for a detector of a cubic kilometer size. In a recent search for a diffuse flux of neutrinos [5], the use of a full MC simulation limited the number of generated atmospheric muons at 63 equivalent detector days to represent a background for 807 active days of data.

In order to save the big effort of computing time, a fast Monte Carlo generator is therefore essential. Some parameterizations for the underwater/ice flux and energy spectrum are available in literature [6], [7], [8]. None of them, however, gives the possibility to simulate two or more muons produced in the same CR interaction (muon bundle). In this paper the event generator MUPAGE is presented. It is based on parametric formulas and takes into account the multiplicity of muon bundles.

II. SIMULATION OF ATMOSPHERIC MUON BUNDLES

Parametric formulas are derived in [1], [2] and describe the flux, the angular distribution and the energy spectrum of underwater/ice muon bundles. The muon flux and energy spectrum are parameterized, for the first time, in terms of the bundle multiplicity m .

From these parametric formulas an event generator called MUPAGE (MUOn GEnerator from PArametric formulas) [9] was developed. The program output is a formatted ASCII table containing the kinematics of atmospheric muon bundles on the surface of a *can*. The *can* (Fig. 1) is an imaginary cylinder surrounding the active volume of any proposed detector between

1.5 and 5.0 km of water equivalent depth. The output table with the event kinematics can be used as input for the following steps of the detector-dependent MC simulation, which include the production of Cherenkov light in water or ice and the simulation of the signal in the detection devices as photomultiplier tubes.

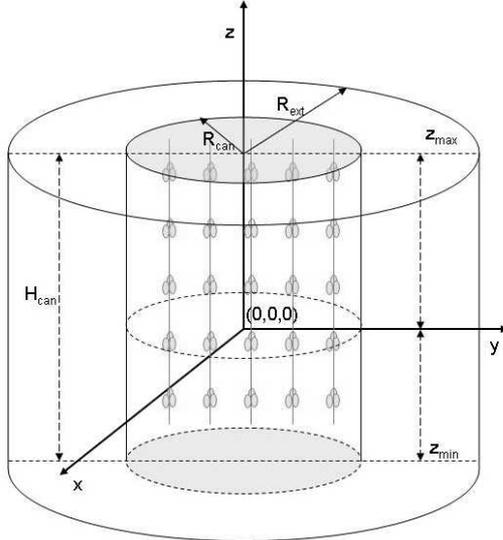


Fig. 1: Sketch of some input parameters. The cylinder surrounding the instrumental volume is the *can*, with radius R_{can} and height H_{can} . The events are generated on an extended can with R_{ext} . The origin of the coordinate system does not have to be located at the center of the detector. The lower disk is at a depth H_{max} with respect to the sea/ice surface.

The code is available in a *tar* archive [9] or by sending a request to the authors.

III. MUPAGE STRUCTURE

The MUPAGE code is written in C++ and it has been tested with gcc version 3.2.x., 3.4.x and 4.1.x. The program requires ROOT libraries [10] for the pseudorandom number generator. The *tar* archive contains the code, the Makefile, a README file, two template script files (for tcsh and for bash) to launch the executable and some subdirectories. After compilation, the executable and a Linux/ directory, containing the object files, are created. The core classes are contained in directories *inc/* and *src/*, which do not need to be changed by the user.

The simplest way to execute MUPAGE is to use, for tcsh, the C-shell script file *run-mupage.csh*, or, for bash, the Shell script file *run-mupage.sh*. Here, the user can modify the random seed, the run number and the number of events to be generated N_{gen} .

The flowchart of the Monte Carlo program is shown in Fig. 2. The bundle multiplicity, direction and impact point of the shower axis on the *can* surface are generated first. According to the depth-zenith angle-intensity relation, this event can be accepted or rejected, using a standard Hit-or-Miss method. Once selected, if the event

is a single muon, the energy is sampled from the energy distribution expected for that specific depth and zenith angle. If the event is a multiple muon, for each muon the radial distance R from the shower axis is sampled, followed by the muon energy (which depends also on R). The impact point of each muon in the bundle is the projection on the *can* surface of its position on the plane perpendicular to the shower axis, where it has been generated. Consequently, since all muons in the bundle are assumed to reach that plane at the same time, also the arrival time of each muon on the *can* surface is computed. Details are given in [9]. Since the multiplicity m of the bundle is generated according to the muon flux, it can happen that some muons in the bundle do not geometrically intercept the *can* surface and therefore they are not written in the output file.

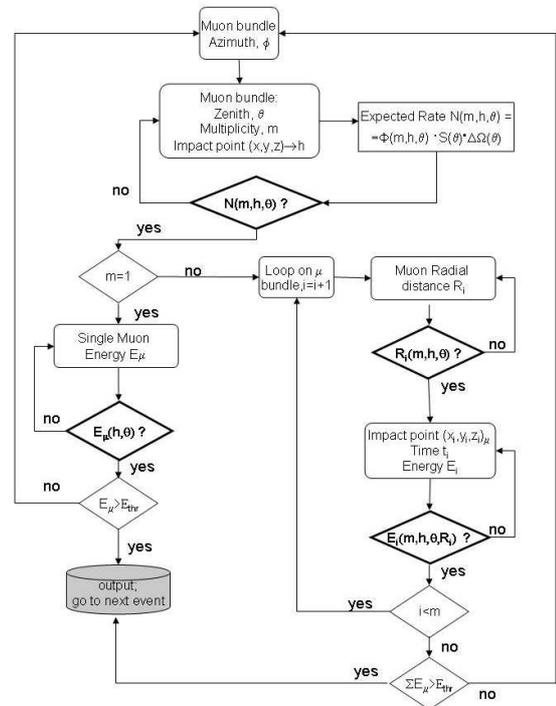


Fig. 2: The flowchart of the MUPAGE event generator. The smooth-angle rectangles indicate the extraction of uniformly distributed random values. The decisional rhombuses in bold select values according to formulas reported in [1], with a Hit-or-Miss method. The procedure is iterated for N_{gen} events.

A. Description of the input file

The generator needs some parameters as input: the dimensions and depth of the *can* surrounding the detector (see Fig. 1), the density of the detector medium and the ranges of the various simulation parameters (e.g. multiplicity, zenith angle, muon energy). The user can change the default values which refer to a production done for the ANTARES experiment. The main parameters are: **Hmax** (2.475 km): vertical height of the sea/ice level with respect to the *can* lower disk; **Zmin** (-278.15 m): position of the *can* lower disk in the detector frame, **Zmax** (313.97 m): position of the

can upper disk. The *can* height is defined as: $H_{can} = Z_{max} - Z_{min}$;

Rcan (238.61 m): *can* radius; **EnlargedCanR** (100 m): *can* radius extension;

density (1.03 g cm⁻³): mean value of the density of the detector medium (ice or water) to convert **Hmax** in km.w.e.;

THETAmin (0°), **THETAmax** (85°): minimum and maximum value of the zenith angle range;

MULTmin (1), **MULTmax** (100): minimum and maximum value of bundle multiplicity range;

Rmax (100 m): maximum muon lateral spread with respect to the shower axis;

Emin (0.02 TeV), **Emax** (500 TeV): minimum and maximum muon energy range;

Ethreshold (0.02 TeV): the minimum energy threshold of all muons combined in the event bundle.

The radius of the generation volume is increased by the quantity **EnlargedCanR** in order to accept also muons very far from the shower axis. Since one of the aims of the code is to save computing time, the user is encouraged to set the same value for **EnlargedCanR** and **Rmax**.

An example of usage of parameter **Ethreshold** is given in Sect. IV-A.

B. Description of the output files

The output file (**\$OUTFILE1** in the template script) contains all information about the generated events in a formatted ASCII table. An example of an output data file with 1000 generated events (`run_01.evt`) can be found in the *tar* archive. Each line of the table contains the following information:

evt_id m track_id x_i y_i z_i v_x v_y v_z E_i t_i G_{id}

where:

- **evt_id** is the event number;
- **m** is the multiplicity of the muon bundle at the depth where the shower axis hits the *can*;
- for each muon m_c in the bundle intercepting the *can* ($m_c \leq m$):
 - *track_id* = i ($i = 1, m_c$) is the muon identifier in the event;
 - (x_i, y_i, z_i) are the coordinates [in m] of the muon impact point on the *can* surface;
 - (v_x, v_y, v_z) are the direction cosines of the muon, coincident with those of the bundle axis;
 - E_i is the energy [in GeV] of the muon;
 - t_i is the time delay [in ns] of the i -th muon at the *can* surface with respect to the first muon ($i = 1$). t_i can be either positive or negative;
 - G_{id} is the GEANT particle identification number (6 = μ^- by default).

The livetime and its statistical error (see Sect. III-C) corresponding to the total number of simulated events N_{gen} is written in a second file (**\$OUTFILE2**).

Note that there is no bias or ordering (in energy, multiplicity and zenith angle) in the simulation. All events have the same weight so the output file reproduces

a real data file. A disadvantage of this approach is that since all the input physics parameters (primary CR flux, interaction models, muon transport) are fixed, the events cannot be re-weighted.

C. Equivalent livetime of the simulation

From N_{gen} , the equivalent livetime of the run is automatically calculated. Since the flux of muon bundles of a given multiplicity m is known for each value of depth H at a given zenith angle ϑ_i , the expected rate on the *can* upper disk at the depth $H = H_{min}$ is:

$$\dot{N}_{MC}(\Delta\Omega_i) = \Phi(H_{min}, \vartheta_i, m) \cdot S \cdot \Delta\Omega_i \quad [\text{s}^{-1}]$$

where, $\Delta\Omega_i = 2\pi(\cos\vartheta_{1i} - \cos\vartheta_{2i})$ is the solid angle centered at $\vartheta_i = (\vartheta_{1i} + \vartheta_{2i})/2$, and $S = \pi R_{ext}^2 \cos\vartheta_i$ [m²] is the projected area of the upper disk. The equivalent livetime is computed from the number of generated events $N(\Delta\Omega_i)$ on the upper disk in the solid angle $\Delta\Omega_i$ as:

$$T(\Delta\Omega_i) = N(\Delta\Omega_i) / \dot{N}_{MC}(\Delta\Omega_i) \quad [\text{s}]$$

The livetime is computed as the weighted average on 33 different solid angle regions of $T(\Delta\Omega_i)$, which have the same value, within statistical errors, and are written in the **\$OUTFILE2** file.

IV. EXAMPLES AND APPLICATION

The development of MUPAGE was motivated by the need of a large sample of atmospheric muons in order to simulate the response and the possible background for the neutrino studies in the ANTARES and NEMO Collaborations and moreover to study possible detector geometries for the future cubic kilometer detector in the Mediterranean Sea, on behalf of the KM3NeT Consortium. Although a full Monte Carlo simulation is also available [11], MUPAGE offers the possibility of a faster simulation. Some examples of the MUPAGE performance are presented.

A. Usage in the ANTARES Collaboration

The ANTARES neutrino telescope [12] has been taking data since March 2006 and it has been completed in May 2008. During the first 6 months of operation, in its one line configuration, measurements of atmospheric muons from data are taken. For this first analysis, two samples of atmospheric muon bundles with different multiplicity ranges are generated using MUPAGE: for $m = 1 - 30$, the 8.8×10^8 generated events correspond to a detector livetime of 11.7 days; and for $m = 31 - 1000$, the 8×10^6 generated events correspond to 32.4 equivalent detector days. After the MUPAGE kinematics generation, muons are propagated inside the *can*, where the emission of Cherenkov light and the production of signals in the photomultiplier tubes (PMTs) are simulated with a software package [11] which needs a computing time almost a factor 10 larger than that required by MUPAGE. The two samples are

used to investigate the efficiency of the track reconstruction method, reproducing the time and the angular residuals very well, and to measure the vertical muon intensity versus depth [13], in good agreement with other published values. In particular for the latter goal, the MUPAGE simulation was used to convert the measured rate of reconstructed tracks to the single muon intensity.

For the 5 line configuration of the ANTARES detector, in 2007, MUPAGE is used to generate a data set with livetime of one month. This production is split into 322 files (< 2 GB each). Each file contains 10^7 events, corresponding to 8060 ± 3 s. The computing time needed to produce a file (on a 2xIntel Xeon Quad core, 2.33 GHz) is less than 2 hours. This MUPAGE data set is used to compare the zenith and azimuth angle distributions of reconstructed tracks with the real data and with a CORSIKA full Monte Carlo simulation [14]. A preliminary comparison between data and MC of electromagnetic showers produced by high momentum muons is also performed [15]. The MUPAGE simulation enables the development of a deconvolution method which to be applied to the real data in order to obtain the experimental atmospheric muon flux as a function of the sea depth [16].

The same MC data set is additionally used to estimate the background rate induced by simultaneous muon bundles originating from different cosmic rays. If two atmospheric muons arrive during a trigger window, the produced signals on the PMTs cannot be distinguished from each other. In particular, the timing patterns of the light from the two tracks can be such that the reconstruction result is a single upward going track. The rate of triggering ‘coupled events’, which reach the 5 line ANTARES detector within a time window smaller than $4 \mu\text{s}$, is about 7×10^{-4} Hz. However, no events are reconstructed as upward going, fixing the 90% confidence level upper limit at 9×10^{-7} Hz.

A third data set is produced for the background study of the high energy neutrino diffuse flux (above 100 TeV). In order to optimize the computing time, a (conservative) cut on the minimum energy threshold of all muons combined in the bundle is applied, $E_{thr} > 3$ TeV, and the event multiplicity is divided in several ranges, split is 852 files. The total computing time is 232 hours with a livetime of one year.

B. Usage in the NEMO Collaboration

The NEMO Collaboration has looked for an optimal site for the installation as well as for the development of technologies for an underwater cubic kilometer experiment. The NEMO Phase-1 project, operating from December 2006 to May 2007, has allowed a first validation of the feasibility of cubic kilometer detector [17]. A small MUPAGE MC data set is produced, generating 4×10^7 events corresponding to ~ 11.3 equivalent hours. The MC simulation of zenith and angular distribution of reconstructed tracks is used for the comparison with 11.3 hours of data taking, giving an excellent agreement [18].

C. Usage in the KM3NeT Consortium

The KM3NeT Consortium aims at the definition of a complete project for an underwater cubic kilometer neutrino telescope to be installed in the Mediterranean Sea [19]. Since the final detector performance will depend critically on the rejection of atmospheric muons, MC simulations for different detector geometries as a function of site depth are performed. For example, a small MUPAGE MC data set with a livetime of 105 min is used to study the response to atmospheric muons for different PMT orientations [20].

V. CONCLUSION

MUPAGE is a fast generator of the kinematics of atmospheric muon bundles. It uses parametric formulas, valid in the interval $1.5 \leq h \leq 5.0$ km water equivalent and $\vartheta \leq 85^\circ$, for the flux of single and, for the first time, multiple muons. The simulation of the energy spectrum of single and multiple muons takes into account the dependence of the muon energy on the shower multiplicity and the distance of the muon from the shower axis. The generator, developed to minimize the computing time, represents a useful tool for underwater/ice neutrino telescopes for the production of a large amount of simulated data. The code is currently used for the Monte Carlo simulation of atmospheric muons on behalf of the ANTARES and NEMO Collaborations. Furthermore, the KM3NeT Consortium is using the code to study the atmospheric muon rejection performances of different detector geometries.

REFERENCES

- [1] Y. Becherini *et al.*, *Astrop. Phys.* **25**, 1 (2006).
- [2] M. Spurio *et al.*, these proceedings.
- [3] M. Ambrosio *et al.*, MACRO Collaboration, *Phys. Rev. D* **56**, 1407 (1997); *Phys. Rev. D* **56**, 1418 (1997).
- [4] D. Heck *et al.*, Report FZKA6019 (1998), Forschungszentrum Karlsruhe.
- [5] A. Achterberg *et al.*, *Phys. Rev. D* **76**, 042008 (2007).
- [6] A. Okada, *Astrop. Phys.* **2**, 393 (1994).
- [7] E.V. Bugaev *et al.*, *Phys. Rev. D* **58**, 054001 (1998).
- [8] S.I. Klimushin *et al.*, *Phys. Rev. D* **64**, 014016 (2001).
- [9] G. Carminati *et al.*, *Comput. Phys. Commun.* **179**, 915 (2008); arXiv:0802.0562 [physics.ind-det] (2008).
- [10] R. Brun and F. Rademakers, *Nucl. Instrum. Methods A* **389**, 81 (1997); see also <http://root.cern.ch>
- [11] J. Brunner (Antares simulation tools), in: Proceedings of the VLVnT Workshop, October 5-8, 2003, Amsterdam. <http://www.vlvnt.nl/>
- [12] G. Carminati (for the ANTARES Coll.), in: Proceedings of the Rencontres de Moriond 2009 EW session, La Thuile. arXiv:0905.1373 [astro-ph] (2009).
- [13] M. Ageron *et al.*, ANTARES Collaboration, *Astrop. Phys.* **31**, 227 (2009).
- [14] A. Margiotta (for the ANTARES Coll.), *Nucl. Instrum. Methods A* **602**, 76 (2008).
- [15] S. Mangano (for the ANTARES Coll.), *Nucl. Instrum. Methods A* **588**, 107 (2008).
- [16] M. Bazzotti (for the ANTARES Coll.), these proceedings.
- [17] A. Capone *et al.* (NEMO Collaboration), *Nucl. Instrum. Methods A* **602**, 47 (2009).
- [18] I. Amore (for the NEMO Coll.), *Nucl. Instrum. Methods A* **602**, 68 (2009).
- [19] KM3NeT Consortium: <http://www.km3net.org>
- [20] P. Sapienza *et al.*, *Nucl. Instrum. Methods A* **602**, 101 (2009).