Ultra-high energy neutrino simulations

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Publication date
2009

Document Version
Final published version

Appendix B

Implementation of ANTARES in MMC

The various media implemented in MMC are assumed to be concentric spheres centered at the center of the Earth, each having different densities. These spheres are surrounded by a main medium which fills all space. The Earth's radius is assumed to be $R_T = 6.3713 \times 10^6$ meters, the bedrock lies at $b_0 = -2475$ meters below sea level at the ANTARES site. No additional bed elevation ($z_0 = 0$) of the rock is assumed. The center (of gravity) of the ANTARES telescope is at a depth $D = 2.196849 \times 10^3$ meters. The sea water above the detector center has a smaller density ($1.0291 g.cm^{-3}$) than the water below ($1.0404 g.cm^{-3}$). For ANTARES, three spheres define the Earth which is enclosed inside air. The first sphere with the radius of the Earth defines the sphere for the sea water at the ANTARES site above the telescope center. This sphere extends down to $z = 2.196849 \times 10^3$ meters. The second sphere contains for the sea water at the ANTARES site below the detector center. Its radius is $6.3713 \times 10^6 - 2.196849 \times 10^3 = 6.369103151 \times 10^6$ meters. The sphere passes through the center of the telescope which defines the origin of the altitudes $z = 0$ in the MMC geometry. The third and last sphere is the seabed rock below the detector and consist of standard rock. The radius of the sphere is $6.3713 \times 10^6 - 2475 = 6.368825 \times 10^3$ meters. The sphere goes through $z = -278.151$ meters. MMC uses a media definition file in which the rock and sea water surrounding ANTARES are detailed. Such a file can be defined as follows:

```
# media definition file
# include with -mediadef=[this file]
# use the following syntax:
# all        det vcut ecut conti rho medium
# sphere z r det vcut ecut conti rho medium
all                          0 0.05 5.e2 1 1.0      Air
sphere  2196.840 6371300     0 0.05 5.e2 1 0.99456  Antares Water
sphere     0     6369103.151 1 0.05 5.e2 1 1.0      Antares Water
```

```
sphere  -278.151 6368825     0 0.05 5.e2 1 1.0      Standard Rock
```

A new medium (Antares water) was implemented in MMC with the properties of the Mediterranean sea water at the ANTARES site. In Figure B.1, the distribution of the final energy of the muons that crossed 300 meters of Antares water with a fixed initial energy equal to 100 TeV is shown. Several values of ν_{cut} were used to determine which relative energy cutoff would give the most accurate results. For higher ν_{cut}, the muon spectra are not continuous, but present a peak at the energy E_{peak} which is separated from the distribution by at least the value of $\nu_{cut} \times E_{peak}$. This is a known behaviour of MMC. In order to be able to use MMC with high ν_{cut}, a continuous randomisation feature was introduced. The results when applied to the ANTARES water are shown on Figure B.2. As can be seen on the figure, the distributions have become continuous, but converge faster than those without the continuous randomisation option. In order to bring the number of separate energy loss events to a reasonable value and therefore to increase the running speed, when using MMC with ANTARES we will use a rather high value of the relative energy cutoff ($\nu_{cut} = 0.05$) with the continuous randomisation feature.

The salinity of the water has been measured to be 38.44 ± 0.02 g.kg^{-1} at the ANTARES site whereas it was cited as 35.0 g.kg^{-1} in [115] for sea water in general. Therefore the chemical composition of the water at the ANTARES site is the same as the water defined in [115] but with different densities for the elements containing salt. The chemical composition of the sea water at the telescope site is defined in [82]. The values of the density of the main water elements are shown in Table B.1.

Atomic Symbol	Atomic Number (Z)	Atomic Weight (A)	Percent by weight
H	1	1.0	2.0
0	8	15.999	1.00884
N_a	11	22.99	$9.43.10^{-3}$
K	19	39.10	$2.09.10^{-4}$
M_g	12	24.31	$10.87.10^{-4}$
C_a	20	40.08	$2.09.10^{-4}$
C_l	17	35.45	$1.106.10^{-2}$
S	16	32.07	$5.82.10^{-3}$

Table B.1: *Chemical composition of the sea water at the ANTARES site.*

MMC reads and outputs data in the AMANDA ASCII F2000 compliant format to and from the standard input and output so the events can be passed to the detector simulation. The F2k output format can be translated into the ANTARES event ASCII format to process the output of MMC with the ANTARES detector simulation and analyse the Monte Carlo data with the help of the main trigger

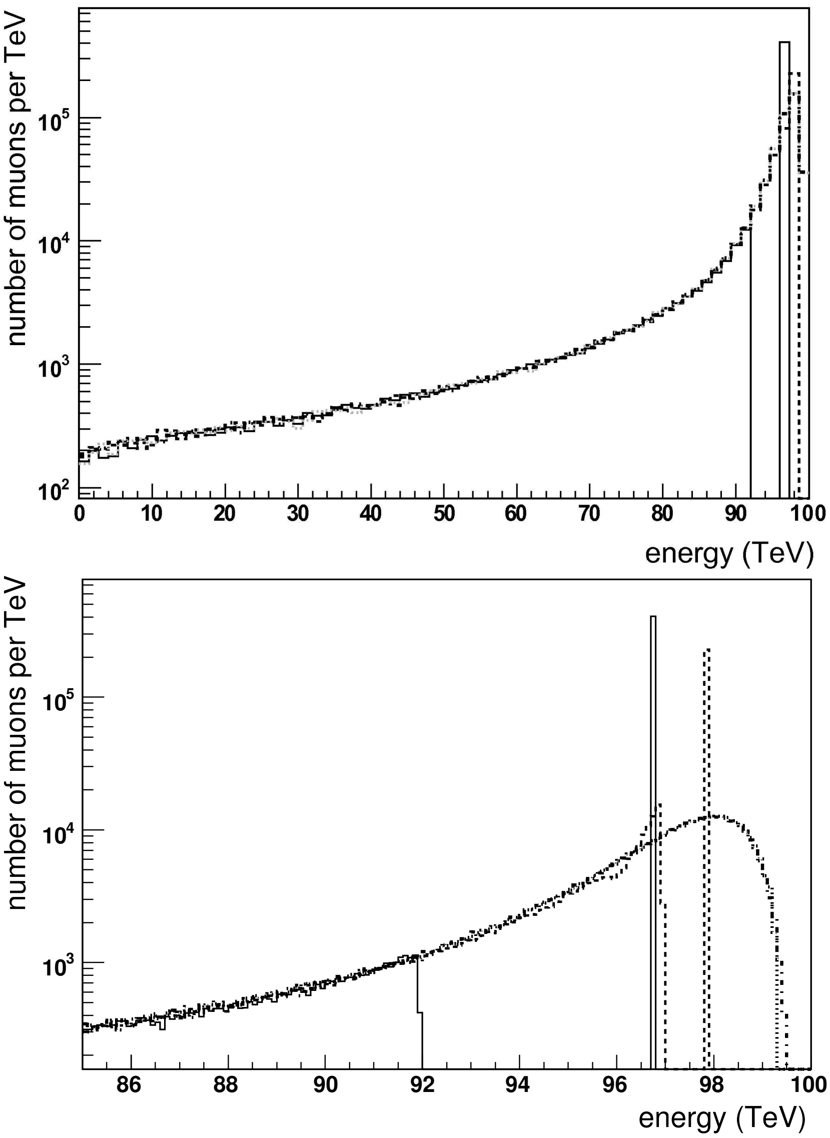

Figure B.1: *Comparison of the final energy distributions of* 10^7 *muons with initial energy* 100 *TeV which were propagated through* 300 *meters of ANTARES Water, calculated by MMC with an energy cutoff* $v_{cut} = 0.05$ *(solid line),* $v_{cut} = 0.01$ *(dashed),* $v_{cut} = 10^{-3}$ *(dotted) and* $v_{cut} = 10^{-4}$ *(dashed-dotted). On the right is a close-up on the left figure.*

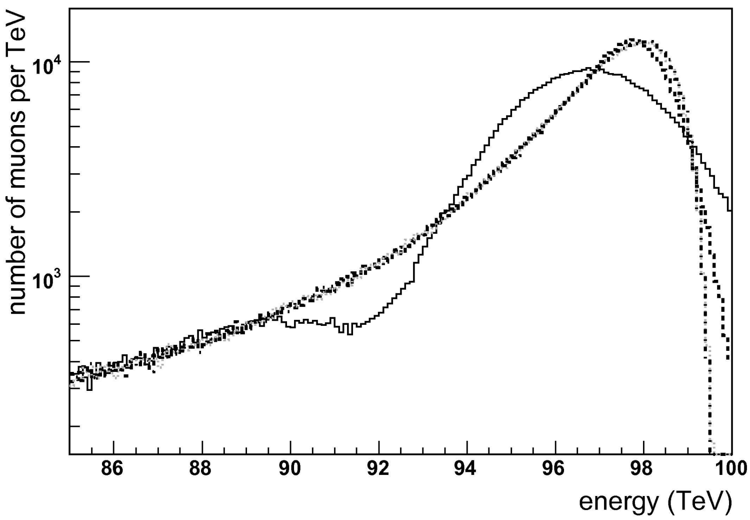

Figure B.2: *Same as the right part of Figure B.1 but with the continuous randomisation option which is used to prevent muon spectra to be not continuous for high* v_{cut}.

software (see Chapter 3). The ANTARES event ASCII format makes use of tags defined to make the Input/Output (IO) of the Monte Carlo data compatible with the ROOT framework which allows to analyse the data in a more efficient way. A detailed description of the ANTARES event tags which exist for Monte Carlo simulated data can be found in the internal note [65].