TIERRAS: an AIRES package to simulate High Energy Cosmic Ray Showers Underground and Underwater

Matias Tueros[*][†]**, Sergio Sciuto**[*][†]

[*]*Depto. de Física, Fac. de Cs. Ex., Universidad Nacional de La Plata, CC 67 (1900) La Plata, Argentina*
[†]*IFLP - CCT La Plata - CONICET, Casilla de Correo 727 (1900) La Plata, Argentina*

***Abstract*.** **In this communication we present TIERRAS, an extension for the AIRES cosmic ray extended air shower simulation program that enables the four dimensional propagation of a cosmic ray particle cascade underground, under-ice or underwater up to energies of 1 ZeV and depths of 3 kilometers. TIERRAS was developed as a new simulation tool for shallow underground muon detectors but it evolved to cover the shower simulation needs of almost every type of ultra high energy cosmic ray or neutrino experiment. Results are checked against experimental measurements on underground laboratories and compared with other particle propagation codes, such as FLUKA or Geant4. The first results of full underground shower simulations are presented, including an example for shallow underground detectors and another for hadron showers induced by neutrinos having its first interaction in water, to be used on neutrino telescopes on water or Ice. The idea to use TIERRAS to track particles exiting the ground either as albedo of an incoming cosmic ray shower or from underground initiated showers, of great interest for projected orbiting detectors, is also discussed.**

***Keywords*:** **Simulations, Underground detectors, Under-water detectors, Cosmic Rays**

I. INTRODUCTION

Muons are usually called the "penetrating component" of cosmic ray induced Extended Air Showers (EAS). Due to their small cross section, high energy muons are able to reach deep underground without interacting in the atmosphere, carrying information about the primary particle mass, the inelastic cross section and other physical properties of the processes that originated them. To tackle these problems many shallow underground detectors studying the total muon content, muon multiplicity, and muon lateral distribution function have been successfully used(AGASA, CASA-MIA, MINOS) and more are going to be built (AMIGA).

To aid in the interpretation and design of this type of experiments we present TIERRAS, an extension of the well known AIRES [1] simulation code that has been originally designed to continue the EAS simulation underground and study the design and performance of the AMIGA detectors but quickly showed its potential for other underground experiments. TIERRAS can also be useful to study the phenomenology of underground showers, and explore the signatures that exotic decays or interactions could present in underground detectors.

Throughout this document we will use the term "underground", to refer to rock, soil, water, ice or even moon regolith environments. The material composition is not relevant for the discussion given in this article, and all these media can be simulated in TIERRAS.

II. UNDERGROUND SIMULATIONS

The algorithms needed to simulate the propagation of high energy particles through matter are virtually independent of the state of aggregation of the medium through which particles propagate, as are the physical routines needed for the calculation of energy losses or for the evaluation of the collision products. In the energy range of interest in cosmic ray showers, the main dependences of physical processes are the mass and the charge (of the projectile and the target) and the medium density. This makes it possible to take a simulation software used to propagate particles on air and adapt it to simulate interactions in other media.

The public domain AIRES code has been extensively used by many scientists around the world for the past ten years, becoming one of the standard simulation codes in the high energy cosmic ray field.Important aspects of AIRES physical routines, it results and comparison against experimental data have been discussed in [2] [4] [3] [5] and [6].

Although most algorithms in AIRES are independent of the media, some major differences in the phenomenology of particle showers are introduced by the change from air to ground. For example, Pions in air have a high chance of decaying instead of interacting with other hadrons, producing high energy muons and neutrinos. In the higher density of underground environments pions are more likely to interact, giving rise to a higher amount of hadronic particles, in particular neutrons, that can travel relatively long distances. Another effect of the higher density is lowering the threshold energy at which the the Landau-Migdal-Pomeranchuk (LPM) and Dielectric Suppression (DS) effects start affecting the gamma cross section, making gamma rays above some PeV much more penetrating than on air.

The LPM and DS routines where modified in TIERRAS to take this into account. Figure 1 shows the mean free path of 1 TeV to 1 ZeV gammas in TIERRAS simulations, for the three hadronic models currently available. It can be seen how the mean free path starts to
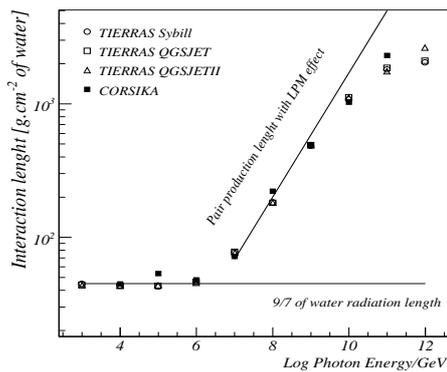
Fig. 1. Mean free path for gammas on water, for different Hadronic interaction models. Dashed lines indicate the expected behavior when only pair production with and without LPM effect is considered. Values for comparison of CORSIKA simulations are taken from [12]
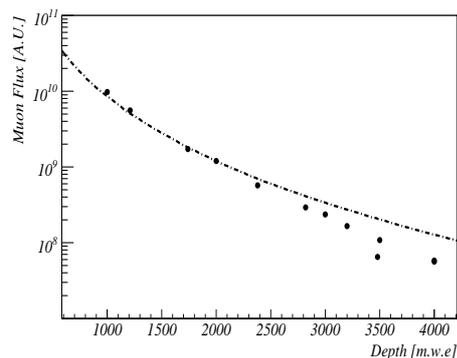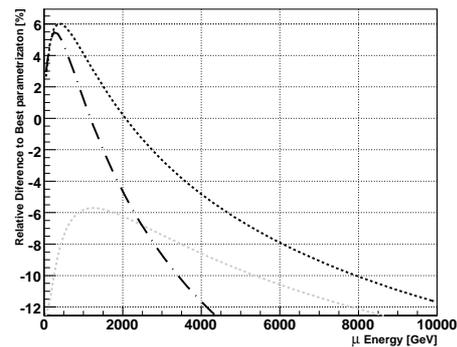

Fig. 2. (Top) Relative difference to the most accurate parametrization of the muon energy loss found in literature [7] vs Energy. The black slash-dot-slash line parametrizes TIERRAS simulations. The light dotted line and the black dotted line are usual parametrizations given in [8].(Bottom) Total muon vertical flux vs. depth. Black slash-dot line is the TIERRAS simulation, black dots are experimental points from Baksan [9] and MACRO [10] experiments.

raise in the PeV region, following the prediction of pair production with LPM up to 1 EeV, were photonuclear processes start to dominate the interaction cross section.

Ionization dominates the energy loss at low energies both in air and rock, and it can be considered fairly constant at energies below 10 GeV. Bremsstrahlung and Pair Production for muons is negligible in air at all but very high energies, while it is increasingly important underground for energies above 50 GeV. Ionization, Bremsstrahlung and Pair production are simulated including the effects of the effective Z , Z/A and medium density, making results accurate for all media.

Photo-production however requires special attention. The original AIRES code does not take into account muon induced spallation [3], and in the current version neither does the TIERRAS package. This will make TIERRAS to underestimate muon energy loss at very high muon energies (above 2 TeV).

Several parametrizations of the muon energy loss are available on the literature [7] [8]. To show the effect that the omission of photo-production processes has on muons, the mean energy loss per $g.cm^{-2}$ was calculated and compared with the reference parametrizations in Figure 2 (Top).

It can be seen that TIERRAS has good agreement (below 6%) with these parametrizations up to around 2 TeV, where the effect of muon induced spallation starts to be important. As the muon spectrum underground is so steep, a difference of a few percent in the energy deposit has a great impact in the total muon flux at a given depth. To see how this affects muon propagation underground in TIERRAS, we simulated the vertical muon flux at different depths using a parametrization of the muon flux at the earth surface [8]. Comparison with measurements from Basin [9] and the MACRO experiment [10] are shown in Figure 2.

We see that for very deep sites (below 2.5 kilometers of water equivalent, corresponding also to a 2 TeV mean muon energy), our results depart from the experimental data, showing the limit to which this simulation code

can be used for this kind of applications. This of course is not a limitation for cosmic ray studies in shallow underground sites. The energy spectrum of the muons produced in an EAS peaks between 1 and 500 GeV and particles of more than 1 TeV have almost no influence on the total muon signal.

If calculation of the total flux is not a concern, TIERRAS can be used for deeper sites without problems with enough confidence. As an example of the validity of the simulations up to 3 km of water, we compared the TIERRAS simulations of 5×10^5 2 TeV muons to the ones made with GEANT4, FLUKA and MUSIC published in [11].

The muon spectrum obtaied at that depth, shows that the agreement between TIERRAS and other codes is very good, given the differences off the different simulation parameters and physical processes present on each code (radiation length, average atomic number, medium composition and density, etc). The survival probability of the simulated muons is reported to be 0.779 (MUSIC), 0.793 (GEANT4) and 0.756 (FLUKA) and is 0.808 in the TIERRAS simulation. The mean energy of the surviving muons is 323 GeV (MUSIC) 317 GeV (GEANT4) and 344 (FLUKA) while it is 367 GeV in TIERRAS.
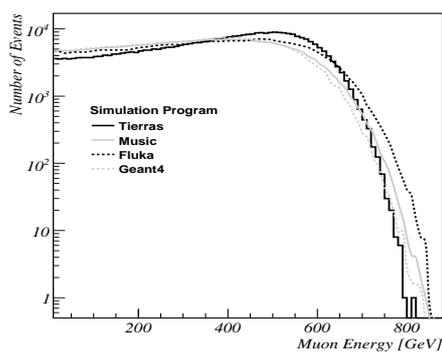
Fig. 3. *Energy spectrum of 2 TeV muons propagated to 3 k.w.e depth in sea water for different simulation codes*

III. EXAMPLE APLICATION ON SHALLOW UNDERGROUND DETECTORS: THE AMIGA CASE

To illustrate the power of this new tool and some qualitative aspects of underground showers, we show here the results of a TIERRAS simulation for a 1 EeV proton air shower penetrating 3 m in "Standard Soil" (proposed AMIGA design [13] [14]).

Primary cosmic rays have their first interaction at high altitudes, and traverse many interaction lengths before reaching ground. As a result, at ground level the energy spectra of the different shower particle types are in dynamic equilibrium and passage through more air would not substantially change it. When the shower reaches ground it encounters an abrupt change in medium density, atomic number and atomic weight that provokes a sudden rearrangement of the particles energy spectra. High energy particles encounter a higher cross section, and a lot of low energy particles are generated until the particles reach a new equilibrium spectrum some interaction lengths later. Note that this is just a redistribution of energy as the energy loss per $g.cm^{-2}$ increases only 30% due to the medium change. The back-scattering cross section is also increased producing a noticeable "albedo" effect, mainly in the shower core where most of the high energy particles reside. These albedo particles are very numerous but have very low energy and are stopped in a few hundred meters in air.

Figure 4 shows how all this phenomena affects the longitudinal development of the different particle types. It is important to note that there are up-going particles at any stage of shower development. As a regular AIRES simulation ends when the particles reach ground, the lower part of the simulation lacks the up-going portion of the shower that should have been generated lower in the ground. This can be seen in Figure 4a as the sudden decrease in particle number in the last 25 $g.cm^{-2}$ before reaching ground level at 875 $g.cm^{-2}$. The profile regains its continuity when albedo particles are added to the AIRES simulation.

Gamma emission from bremsstrahlung of charged particles scales as Z^2 , so the emission is doubled

passing from Z=7.26 in air to Z=11 underground, as most cross sections do. The number of gammas is nearly doubled when changing the medium, but the mean energy reduces indicating again that a lot of low energy emission is occurring. The development of the longitudinal profile of electrons is tightly related to the gammas profile, and shows the same albedo effect on the air/ground interface. As this two are the more numerous particles, the profile of the total number of particles exhibits the main characteristics of this two particle types, and can be seen in Figure 4a.

Figure 4b shows the longitudinal development of muons. It can be seen that there is a great contribution of "albedo" muons, and that the transition is not continuous. The excess muons are secondary muons produced by the decay of other albedo particles, specially pions. This is evident from the fact that the albedo component rises abruptly about 1.5 $g.cm^{-2}$ above ground level, showing that the up-going pions start to decay after exiting ground, reaching the maximum about 40 m above ground. Muons can travel far in air, and the effect on the total number of muons is more than 10% up to 800 $g.cm^{-2}$ or 700 m height. All this up-going muons have relatively little energy (mean muon energy is 0.2 GeV against the 5 GeV of the down-going component), and there is little transfer of energy to the muonic energy content.

The passage trough soil stops most of the electrons and low energy muons, inverting the relation of the muonic and electronic component energies. At ground level, the electrons carry about 5 times more energy than muons.At AMIGA level muons carry more than 10 times more energy than electrons.

Pions endure one of the more important redistributions of energy due to the change in cross section. The increased density underground make pions more likely to suffer an hadronic interaction with a nucleus than to decay as it is normally the case in air, generating a 10 fold increase in their number. Nearly half of the pions generated near the surface exit upwards as albedo, as seen in Figure 4c. Pions on air decay to muons (plus neutrino), explaining the increase in the number of muons seen in the muon albedo.

The great number of nuclear interactions produces an important amount of low energy neutrons underground, as can be seen in Figure 4d. Almost half of the neutrons are produced upwards, and can be very important in simulations of groundlevel or underground neutron monitors. Up-going neutrons carry only 5% of the total neutron energy at ground level, their mean energy being 0.27 GeV, against the 3.3 GeV of the down-going component.

IV. EXAMPLE APPLICATION ON HADRONS PROPAGATION

One of the process though which neutrinos can interact with nuclei in the underground medium are the
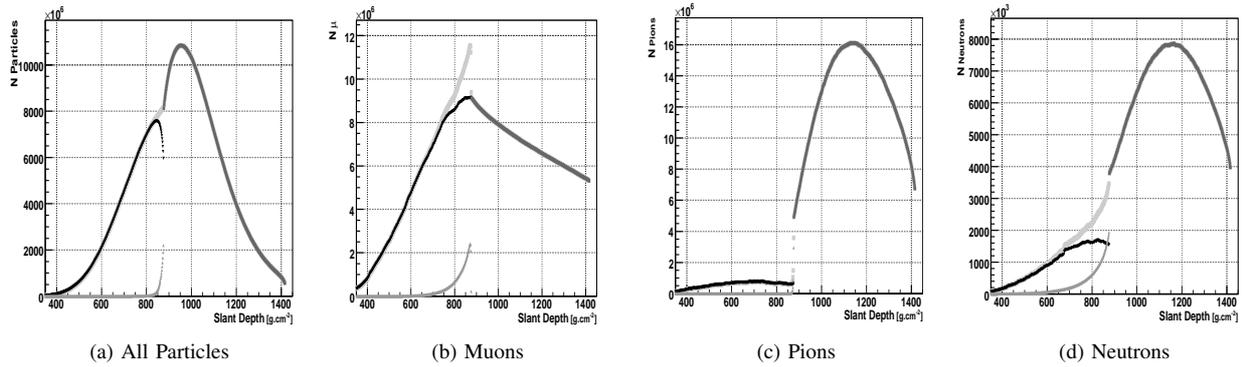
(a) All Particles   (b) Muons   (c) Pions   (d) Neutrons

Fig. 4.   *Longitudinal development for different particle types of a UHECR Proton. Black correspond to AIRES simulation, dark gray to the TIERRAS underground simulation and light gray to the Albedo component. In very light gray AIRES+Albedo components are added.*

charrged current interactions (CC). This type of interactio can produce charged leptons, that can in turn develop an hadronic shower that can be detected. TIERRAS can be used to study the development of such showers, and the signature they would give on underground detectors.

As an example application, Figure 5 shows the comparison of TIERRAS simulations of 10 and 100 TeV protons propagating through 2 m of sea water, with the results presented in [12]. The three set of simulations are compatible within 10% and very good agreement with the thorough GEANT4 simulation, giving a good indication that hadrons are propagated correctly and that the processes not included in our code to save computing time are not important at these energies.

V. CONCLUSIONS

The simulation of cosmic ray showers underground using TIERRAS provides an important tool for designing, calibrating and validating underground experiments. The good agreement with experimental results for muon energy loss assures the applicability for muon content and muon lateral distribution up to 1 km depth (2.5 km water equivalent) and for some aplications even more. For deeper sites, an effort should be made to include muon induced spallation. Including the propagation of neutrinos is also feasible, and both modifications together would render the simulation code useful for very deep neutrino detectors.

First results indicate that albedo effects can be important close to the shower core and deserve more attention. This package can be used to make further studies on this subject, and its possible impact on detectors signal. The rearrangement of the particle spectrum in the first meters of shower development underground also call for detailed simulations on shallow detectors that sample particles from the "out of equilibrium" stage of the cascade.

REFERENCES

[1] S. Sciutto, AIRES 2.6 user Manual, www.fisica.unlp.edu.ar/aires
[2] P.Hansen et al., Phys. Rev. D 71,083012 (2005)
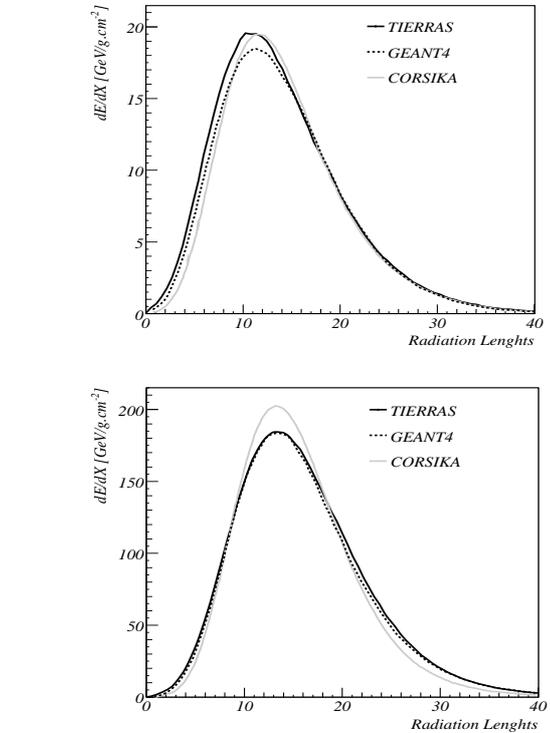[3] A.N. Cillis et al., Phys. Rev. D 64,013010 (2001)

Fig. 5.   *Longitudinal energy deposit profile of 10 TeV (top) and 100 TeV (bottom) protons in 20 m of sea water, for different simulation codes*

[4]   S. Sciutto Proc. 27th ICRC: 237 (2001)
[5]   R. Luna et al. Phys. Rev. D 70, 114034 (2004)
[6]   P.Hansen et al. Phys. Rev. D 68, 103001 (2003)
[7]   Formaggio, Martoff,Annu. Rev. Nucl. Part. Sci. 54, 361-412 (2004)
[8]   T.K. Gaisser,Cosmic Rays and Particle Physics, UK:Cambridge Univ. Press (1990)
[9]   Andreev Yu M, et al., Proc. 16th ICRC (Moscow) 6,200 (1987)
[10] MACRO Collaboration, Phys. Rev. D 52:3793 (1995)
[11] V. A. Kudryavstev, arXiv:810.4635v1
[12] The ACoRNE Collaboration,arXiv:astro-ph/0704.1025v1 (2008)
[13] M.C. Medina et al., Nucl. Inst. and Methods in Phys. Res. A 2006.2:302-311
[14] M.C. Medina et al., American Inst. of Phys. Conf. Proceedings 2007.884:405-410