Computer Physics Communications 181 (2010) 380–392

Contents lists available at ScienceDirect

Computer Physics Communications

www.elsevier.com/locate/cpc

TIERRAS: A package to simulate high energy cosmic ray showers underground, underwater and under-ice ☆

Matías Tueros [a,b,*], Sergio Sciutto [a,b]

[a] IFLP – CCT La Plata – CONICET, Casilla de Correo 727, 1900 La Plata, Argentina
[b] Depto. de Fisica, Fac. de Cs. Ex., Universidad Nacional de La Plata, Casilla de Correo 67, 1900 La Plata, Argentina

ARTICLE INFO

Article history:
Received 27 April 2009
Received in revised form 14 September 2009
Accepted 22 September 2009
Available online 7 October 2009

PACS:
13.85.Tp
07.05.Tp
95.55.Vj

Keywords:
Cosmic rays
Underground laboratories
Monte Carlo simulations
Muon propagation

ABSTRACT

In this paper we present TIERRAS, a Monte Carlo simulation program based on the well-known AIRES air shower simulations system that enables the propagation of particle cascades underground, providing a tool to study particles arriving underground from a primary cosmic ray on the atmosphere or to initiate cascades directly underground and propagate them, exiting into the atmosphere if necessary. We show several cross-checks of its results against CORSIKA, FLUKA, GEANT and ZHS simulations and we make some considerations regarding its possible use and limitations. The first results of full underground shower simulations are presented, as an example of the package capabilities.

Program summary

Program title: TIERRAS for AIRES
Catalogue identifier: AEFO_v1_0
Program summary URL: http://cpc.cs.qub.ac.uk/summaries/AEFO_v1_0.html
Program obtainable from: CPC Program Library, Queen's University, Belfast, N. Ireland
Licensing provisions: Standard CPC licence, http://cpc.cs.qub.ac.uk/licence/licence.html
No. of lines in distributed program, including test data, etc.: 36 489
No. of bytes in distributed program, including test data, etc.: 3 261 669
Distribution format: tar.gz
Programming language: Fortran 77 and C
Computer: PC, Alpha, IBM, HP, Silicon Graphics and Sun workstations
Operating system: Linux, DEC Unix, AIX, SunOS, Unix System V
RAM: 22 Mb bytes
Classification: 1.1
External routines: TIERRAS requires AIRES 2.8.4 to be installed on the system. AIRES 2.8.4 can be downloaded from http://www.fisica.unlp.edu.ar/auger/aires/eg_AiresDownload.html.
Nature of problem: Simulation of high and ultra high energy underground particle showers.
Solution method: Modification of the AIRES 2.8.4 code to accommodate underground conditions.
Restrictions: In AIRES some processes that are not statistically significant on the atmosphere are not simulated. In particular, it does not include muon photonuclear processes. This imposes a limitation on the application of this package to a depth of 1 km of standard rock (or 2.5 km of water equivalent). Neutrinos are not tracked on the simulation, but their energy is taken into account in decays.
Running time: A TIERRAS for AIRES run of a 10^{20} eV shower with statistical sampling (thinning) below 10^{12} eV and 0.2 weight factor (see [1]) uses approximately 1 h of CPU time on an Intel Core 2 Quad Q6600 at 2.4 GHz. It uses only one core, so 4 simultaneous simulations can be run on this computer. Aires includes a spooling system to run several simultaneous jobs of any type.
References:

[1] S. Sciutto, AIRES 2.6 User Manual, http://www.fisica.unlp.edu.ar/auger/aires/.

☆ This paper and its associated computer program are available via the Computer Physics Communications homepage on ScienceDirect (http://www.sciencedirect.com/science/journal/00104655).

* Corresponding author at: IFLP – CCT La Plata – CONICET, Casilla de Correo 727, 1900 La Plata, Argentina.
E-mail address: mjtueros@gmail.com (M. Tueros).

0010-4655/$ – see front matter
doi:10.1016/j.cpc.2009.09.022

1. 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 gather this information many shallow underground detectors studying the total muon content, muon multiplicity, and muon lateral distribution function have been successfully used (AGASA [1]) and more are going to be built (AMIGA [2]).

High energy muons from EAS are also an important source of background noise in deep underground experiments such as particle collider detectors (ATLAS [3]), neutrino physics experiments (MACRO [4], LVD [5]) and beyond standard model experiments (DAMA [6]).

During the design and engineering phase, calibration, results analysis and validation, all these experiments rely on detailed simulations to know the nature, energy distribution, direction distribution, and flux of particles arriving to the detector or the detector location.

In this paper we present TIERRAS, a package originally designed to continue the EAS simulation underground to study the design and performance of the AMIGA detectors that quickly showed its potential to be used in other underground and underwater experiments. The idea behind this package is to speed up and simplify the simulation process by using a single, fast simulation code for the air and underground propagation of particles in the shower cascade, so that its results can be fed directly to the detector simulator with high statistics. TIERRAS is also useful to study the phenomenology of underground showers, and explore the signatures that exotic decays or neutrino interactions could present in underground detectors.

TIERRAS is an extension of the well-known AIRES [7] simulation package, and inherits its features. It is fast, portable and has very small memory requirements. It also has a spooling system to run several simulations at the same time, to take full profit of multiprocessor architectures. As an added benefit this package can use as input already available AIRES simulations libraries, making it possible for the user to save an important amount of computing time.

In this article we will first present the arguments that led us to this approach and some validations of it. We will then describe the software structure and present the installation instructions. We finish with an example of the application of this software to the AMIGA configuration, and end with some conclusions.

Throughout this document, we will refer to the simulations performed underground with AIRES using the TIERRAS package as "TIERRAS simulations" and we will speak about electrons, pions and muons referring to $(e^+; e^-)$, $(\pi^+; \pi^-)$, $(\mu^+; \mu^-)$ respectively. We will also refer to soil, rock, water and ice environments generally as underground environments where the material composition is irrelevant for the discussion.

2. Program validation

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 collision products. In the energy range of interest in cosmic ray showers the relevant parameters for physical processes are the density and radiation length of the medium and the charge and mass of the projectile and the target.

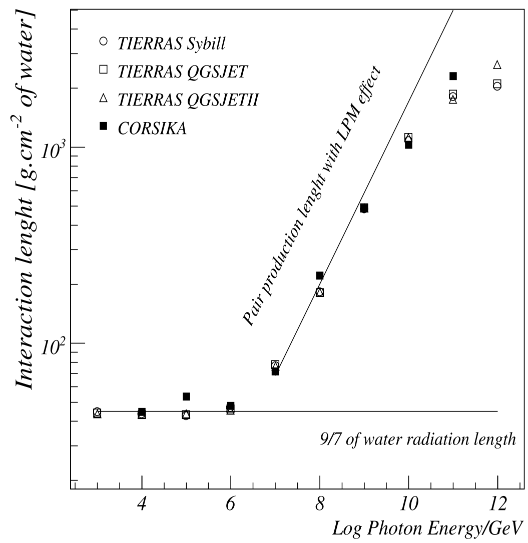


Fig. 1. Mean free path for gammas on water, for different hadronic interaction models. Dashed lines indicate the expected behavior when only pair production with and without LPM effect is considered. Values for comparison of CORSIKA simulations are taken from [17].

This makes it possible to take a simulation software used to propagate particles on air and adapt it to simulate other media even if their state of aggregation are different. For this the software routines to be adapted had to be correctly coded to include the mass, charge and density of the target as input parameters. This is the case of the AIRES code that we have taken as a basis for the TIERRAS package.

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. AIRES provides full space–time particle propagation in a realistic environment, where the characteristics of the medium, the geomagnetic field [8,9] and the Earth curvature are taken into account adequately. Important aspects of AIRES physical routines, its results and comparison against experimental data have been discussed in [10–14] and [15].

Although most algorithms are independent of the media, some major differences in the phenomenology of particle showers are introduced by the change from air to dense media. In air showers electrons are the most numerous particles at ground level while in dense media they are stopped in a very short distance, leaving muons and their secondaries as the only relevant particles after a few meters of material. Pions in air have a high chance of decaying before interacting with other hadrons, producing high energy muons and neutrinos. In the higher density of underground environments, pions are more likely to interact than to decay giving rise to a higher amount of hadronic particles, specially neutrons, that can travel relatively long distances. The higher density also lowers the threshold energy at which 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.

Among all the processes that have been adapted, the ones corresponding to the LPM and DS effects require special mention. A detailed discussion of the LPM effect and its implementation on AIRES is available in [16]. For TIERRAS, the LPM routine was modified to take into account the different densities of underground media and the change in radiation lengths. Fig. 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 raise in the PeV region, following the

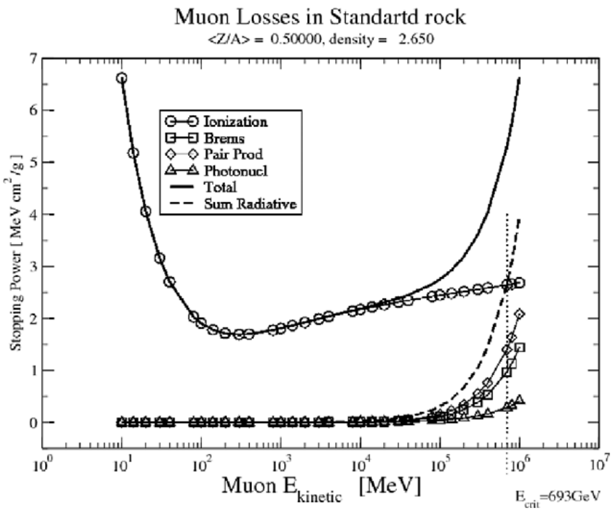


Fig. 2. Muon energy loss vs. energy. Data taken from [19].

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

In the remaining part of this section we will discuss the behavior of some of the observables that have been tested against simulations with other codes and some of the available experimental data, to check our simulation results.

2.1. Muon energy loss

When muons traverse matter they loose energy through ionization, bremsstrahlung, pair production, and photo-production (muon induced spallation). Each of these processes dominates the muon energy loss at different energy ranges and have different relevance in air and underground environments.

Ionization loses dominate at low energies both in air and rock. It can be considered fairly constant at energies below 10 GeV with a value of 1.5 to 2.2 $\mathrm{MeV/g\,cm^{-2}}$ on standard rock.

The critical energy, defined as the energy at which the ionization loss is equal to the radiative losses (bremsstrahlung and pair production), is 3.6 TeV [18] in air and around 0.7 TeV in standard rock (Fig. 2). This makes bremsstrahlung and pair production for muons 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 already simulated in AIRES, including the effects of the effective Z, Z/A and medium density, making results accurate for both rock and air.

Photo-production requires special attention. Once produced, high energy muons cross the entire atmosphere with a negligible probability of suffering a nuclear interaction. For this reason, the original AIRES code does not take into account muon induced spallation [11], and in the current version neither does the TIERRAS package. This will make TIERRAS to underestimate the energy loss rate of muons above some TeV.

The average total muon energy loss rate, varies with energy as

$$-\left\langle \frac{dE(E_\mu)}{dX} \right\rangle = \alpha + \beta E_\mu \tag{1}$$

The α and β parameters are reported to vary logarithmically with energy [20], keeping their ratio fairly constant above 10 GeV and remaining valid at least to 10 TeV. For simpler or not so accurate calculations, fixed values of one or both parameters are often used [21]. To show the effect that the omission of photo-production processes has on muon penetration in the simulations,

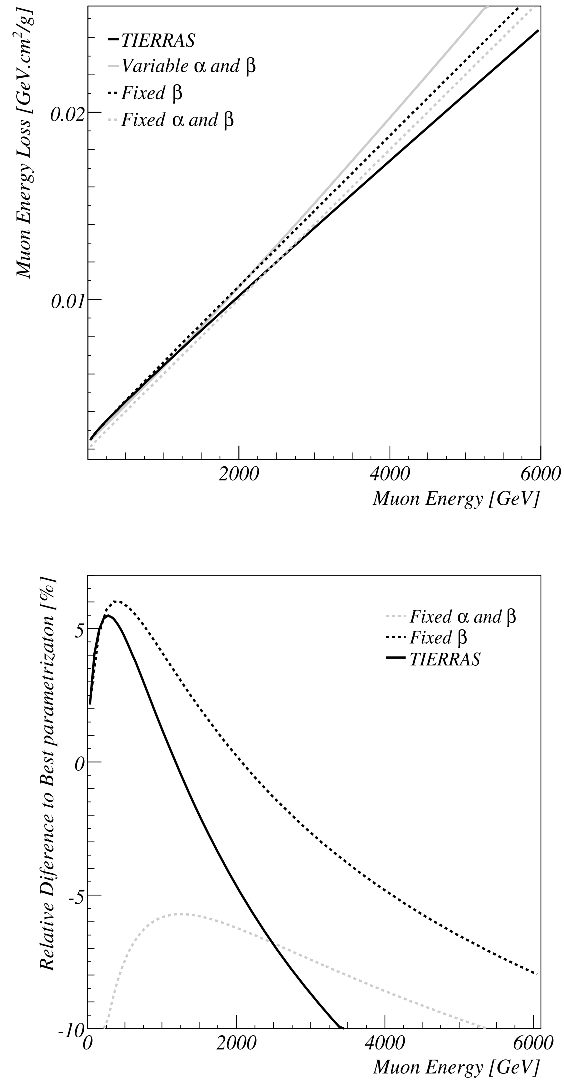


Fig. 3. Muon energy loss vs. energy for different parametrizations (top), and the relative difference to the most accurate parametrization found in literature (bottom).

2×10^6 muons of different energies were propagated through "standard rock". The mean energy loss per $\mathrm{g/cm^2}$ was calculated and is compared with the parametrizations in Fig. 3.

It can be seen that TIERRAS has good agreement with these parametrizations up to around 2 TeV, where the effect of muon induced spallation starts to be important. As TIERRAS simulations slightly overestimate energy deposit at low energies, the effective muon energy at which muons have a range difference higher than 5% is closer to 10 TeV.

For muon flux calculations underground a difference of a few % in the penetration range of muons can lead to significant deviations, as the muon spectrum is very steep. We studied the total vertical muon flux at different depths, and compared it with the measurements made on underground experiments.

The energy spectrum of the muon flux at the earth surface can be parametrized via [21]

$$\frac{dN_\mu}{dE_\mu} \simeq 0.14 E_\mu^{2.78} \left(\frac{1}{1 + \frac{1.1 E_\mu \cos\theta}{115\ \mathrm{GeV}}} + \frac{0.054}{1 + \frac{1.1 E_\mu \cos\theta}{850\ \mathrm{GeV}}} \right) \mathrm{cm^{-2}\,s^{-1}\,sr^{-1}\,GeV^{-1}} \tag{2}$$

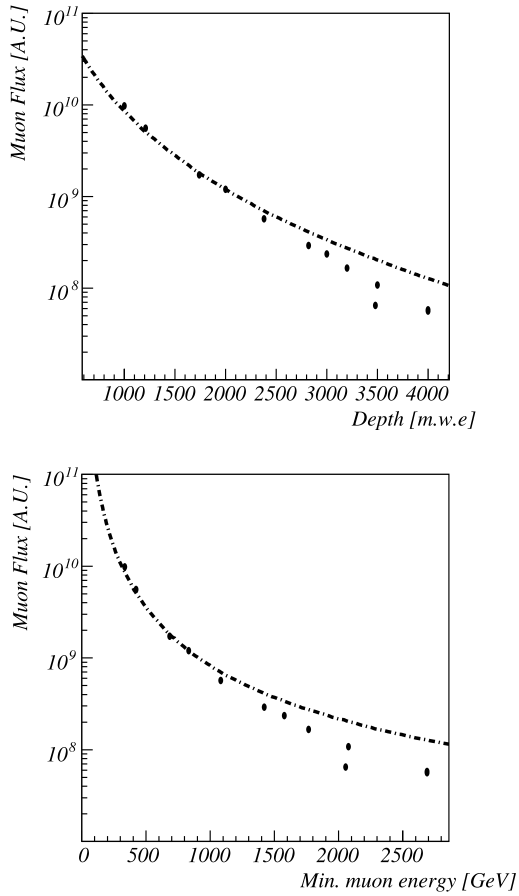


Fig. 4. Total muon vertical flux vs. depth (top) and vs. muon energy depth (bottom). Black slash–dot line is the TIERRAS simulation, black dots are experimental points from Baksan [22] and MACRO [4] experiment. The energy depth is defined as the minimum energy a muon must have at the Earth surface to reach a given depth.

This expression describes the spectral shape with 5% relative errors and a 20% error on total flux in the range from 10 GeV to 100 TeV [21]. A simulation was performed injecting muons following this spectrum, and the results were compared with experimental data from Basin [22] and the MACRO experiment [4] in Fig. 4 (top).

It is clear that beyond 2.5 k.w.e (kilometers of water equivalent $= 10^5$ g/cm^{-2}) the simulated muon flux starts to depart from the experimental value, due to the increased penetration power of muons. This depth corresponds to around 1 km in standard rock.

To check this result, Eq. (1) can be used to loosely calculate the mean depth a muon with a given initial energy will reach, if parameters α and β are considered constant. This means it is possible to convert depth to "minimum muon energy" needed to reach that depth (a lower bound estimation). Using this conversion, we see that 2.5 k.w.e corresponds to around 1 TeV, in agreement with the range of energies in which TIERRAS simulated muons are over-penetrating.

We see then that for very high energy muons underground, photo-production is an important source of energy loss. This limits the use of this package for flux studies of deep underground sites, were the mean energy of muons is around or above 2 TeV. For cosmic ray studies in shallow sites, however, this is no limitation. 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. On experiments interested only in muons far from the shower core like AMIGA, this is even less of a problem. No particle exceeds 500 GeV in a 10^{19} eV shower at

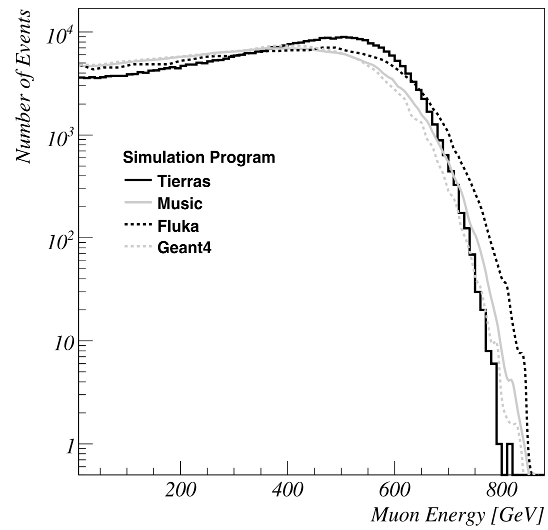


Fig. 5. Energy spectrum of 2 TeV muons propagated to 3 k.w.e depth in sea water.

more than 200 m perpendicular from the shower core. And even if a high energy muon arrives, the effect wont be noticeable as it has to be propagated only some meters until it arrives the detector.

As an example of the validity of the simulations up to 3 km of water, we compare in Fig. 5 the TIERRAS simulations of 5×10^5 2 TeV muons to the ones made with GEANT4, FLUKA and MUSIC published in [23]. It can be seen that although we are taking the muon propagation model to its limits the agreement is good, with a superabundance at high energies due to the lower energy deposit in TIERRAS and the small differences in simulation parameters 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 300 GeV in TIERRAS.

TIERRAS can be successfully used to simulate showers up to 10 k.w.e provided extreme accuracy is not needed. In such a case one needs to take into account that muon range will be affected by an error of about 5%.

It must be noted that, as TIERRAS does not propagate neutrinos and no Tau particles are generated (TIERRAS does not include any kind of Tau physics yet), the applicability of this package for deep neutrino detectors is reduced to the estimation of background signals due to muons. Adding neutrino tracking and tau generation and propagation is one of the top priorities in this package future development, along with the muon nuclear interactions.

2.2. Muon induced neutron energy spectrum

The energy spectrum of neutrons underground is largely uncertain and experimental data is scarce. FLUKA simulations are reported to have good agreement with the LVD experiment data [24]. The spectrum parametrization for the FLUKA simulation for the Gran Sasso site, with a mean muon energy of 400 MeV is presented in Fig. 6, along with the TIERRAS simulation results at the same mean energy.

It can be seen that spectra are very similar at low neutron energies, showing that the processes missing in TIERRAS simulation are not very important at these muon energies. The same level of agreement or better was verified at lower energies and no experimental or simulation data was found to make a suitable comparison at higher energies. For muons with energy in the TeV range or above, when spallation starts to be important, the AIRES

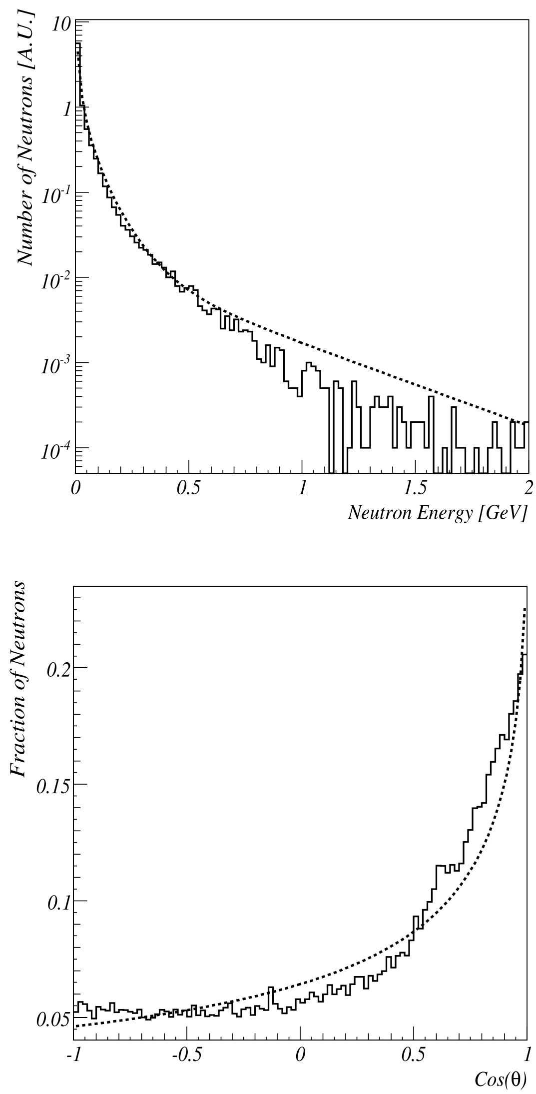


Fig. 6. Comparison of FLUKA parametrization (dashed line) with TIERRAS simulation (histogram) of the muon induced neutron emission for 400 GeV muons. Neutron energy spectrum is displayed at the bottom and neutron direction of motion at the top.

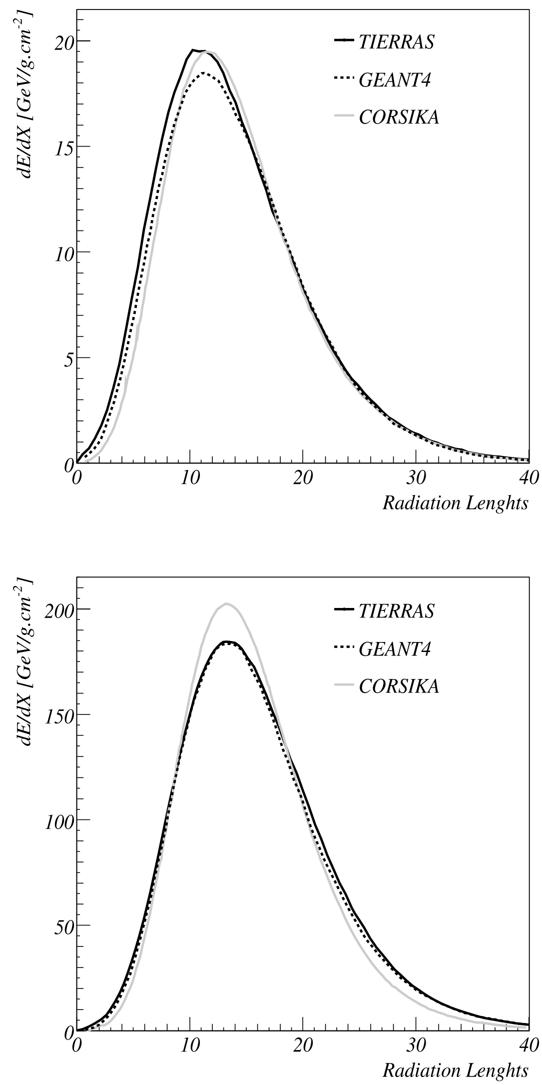


Fig. 7. Longitudinal energy deposit profile of 10 TeV (bottom) and 100 TeV (top) protons in 2 m of sea water, for different simulation codes.

neutron energy spectrum is expected to be softer than a simulation including spallation processes.

2.3. Muon induced neutron angular distribution

Detailed FLUKA simulations [25], based on the experimental results from $\gamma + ^{12}C \rightarrow p + X$ as an approximation for Neutron angular distribution, parametrize neutrons angular distribution with

$$\frac{dN}{d\cos(\theta)} = \frac{A}{(1-\cos(\theta))^{0.6} + B(E_\mu)} \tag{3}$$

where $B(E_\mu) = 0.699 E_\mu^{-0.136}$ and A is normalization constant.

Fig. 6 shows the TIERRAS simulated neutron distribution for 400 GeV muons and the mentioned parametrization. The same level of agreement, or better, is found at lower energies.

2.4. Hadron propagation

Fig. 7 shows the comparison of TIERRAS simulations of 10 and 100 TeV protons propagating through 2 m of sea water, with the results presented in [17]. 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.

2.5. Total electron/positron track length

In the last few years, interest in radio detection of cosmic ray air showers has risen continuously. Large-scale application of the radio technique is under investigation in the framework of LOFAR and the Pierre Auger Observatory [33]. AIRES has already been used with success to calculate radio emission from air showers [32] and the same could be done in TIERRAS for radio emission of underground showers.

Radio emission underground is generated by the negative charge imbalance introduced by Coulomb scattering and knock on processes that inject electrons from the medium into the shower. When the wavelength of the radiation is larger than the dimensions of the shower, the excess charge emission is coherent, and the power is proportional to the square of the shower energy.

An important observable for the simulation of the emission of coherent radio signals from particle showers is the total track length traversed by all electrons and the one traversed by all the positrons. The difference between these quantities is directly related to the amplitude normalization of the electric field and thus

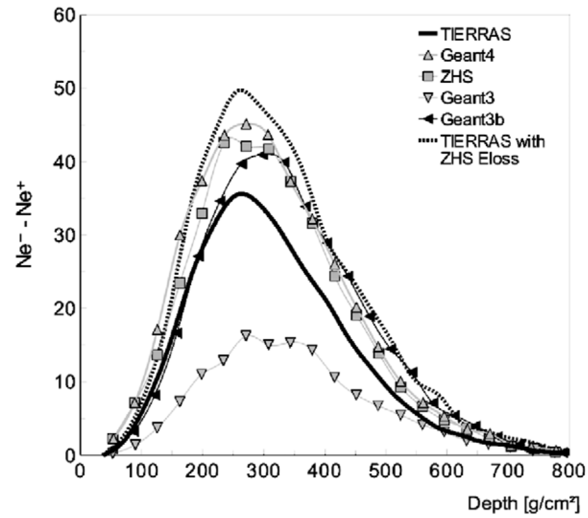
Table 1
Total, total projected and excess projected track length, ratio of excess and number of charged particles at shower maximum (N_{max}) in ice as reported in [31] for various Monte Carlo codes and the ones obtained in TIERRAS and in TIERRAS with same energy deposit parametrization as the one implemented in the ZHS code.

MC code	TIERRAS	TIERRAS with ZHS E_{Dep}	GEANT3	GEANT4	ZHS
Total track (m)	483.4	640.3	577.9	587.9	642.3
Total projected (m)	417.3	538.9	450.0	453.2	516.7
Excess projected (m)	110.8	160.7	123.5	122.7	132.4
Excess/total	0.229	0.251	0.214	0.209	0.206
N_{max}	136	170	142	150	164

with the radio signal intensity. There has been a some controversy regarding this and other related observables due to discrepancies between simulations made with GEANT3, GEANT4 and the ZHS codes. Results presented in [31] showed that the disagreement was due to a configuration parameter set incorrectly in the GEANT3.

Table 1 makes the comparison between the GEANT3 (configured correctly), GEANT4 and ZHS codes with TIERRAS simulations of 100 GeV electron showers. It can be seen that track length values for TIERRAS are around 10 to 15% lower than the ones obtained with GEANT4. Changing the parametrization of the continuous energy deposit in TIERRAS to use the same as the one used in ZHS, results change to resemble the ones obtained with ZHS itself, showing that the energy deposit function is critical for these observables.

Modifying the energy deposit function in TIERRAS also affects the longitudinal development of the number of electrons and positrons and makes TIERRAS results very similar to those of the ZHS code, pointing again the importance of the energy deposit function (Fig. 8). TIERRAS and AIRES use a parametrization of the energy deposit function taken from GEANT3, making the results from both codes more compatible.



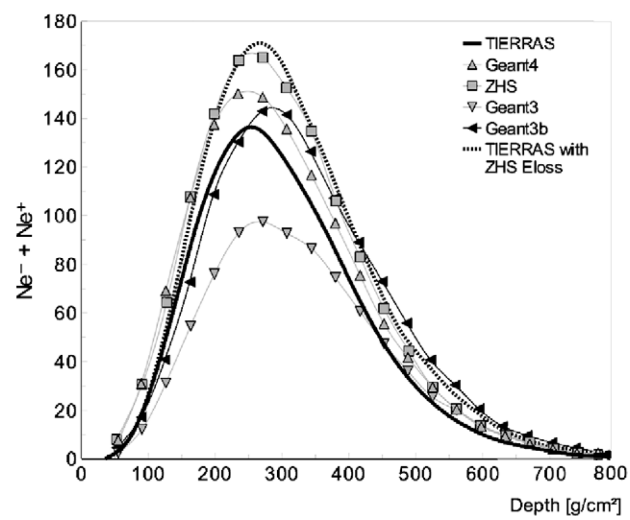


Fig. 8. Longitudinal development of the average number of electrons plus positrons (top) and the number of electrons minus positrons in 100 GeV in Ice for different Monte Carlo codes. GEANT3, GEANT4 are ZHS results are taken from [31]. The dotted line shows the results of a modified TIERRAS with ZHS energy deposit parametrization.

3. Overview of the software structure

In AIRES, the simulation of particle showers is treated in the in the following way:

1. Several data arrays or stacks are defined. Every record within any stacks is a particle entry, and represents a physical particle.
2. The particles can move inside a volume limited by the ground, the injection surface, and by vertical planes which limit the region of interest. For simplicity, TIERRAS uses the same nomenclature. The injection surface (generally the earth surface) is the upper limit and ground (generally underground) is the bottom limit.
3. Before starting the simulations all the stacks are empty. The first action is to add the first stack entry, which corresponds to the primary particle. The primary is initially located at the injection surface, and its direction of motion defines the shower axis. If up going primaries are simulated, like Albedo on TIERRAS the injection will take place at the ground surface instead.
4. The stack entries are repeatedly processed sequentially. Every particle entry is updated analyzing first all the possible interactions it can have, and evaluating the corresponding probabilities for each possibility, taking into account the physics involved.
5. Using a stochastic method, the mentioned probabilities are used to select one of the possible interactions. This selection defines what is going to happen with the corresponding particle at that moment.
6. The interaction is processed: First the particle is moved a certain distance (which comes out from the mentioned stochastic method), then the products of the interaction are generated. New stack entries are appended to the existing lists for every one of the secondary particles that are created. Depending on the particular interaction that is being processed, the original particle may survive (the corresponding entry remains in the stack for further processing) or not (the entry is deleted).
7. When a charged particle is moved, its energy is modified to take into account the energy losses in the medium (ionization).
8. Particle entries can also be removed when one of the following events happens:
   (a) The energy of the particle is lower than a certain threshold energy called cut energy. The cut energies may be different for different particle kinds.

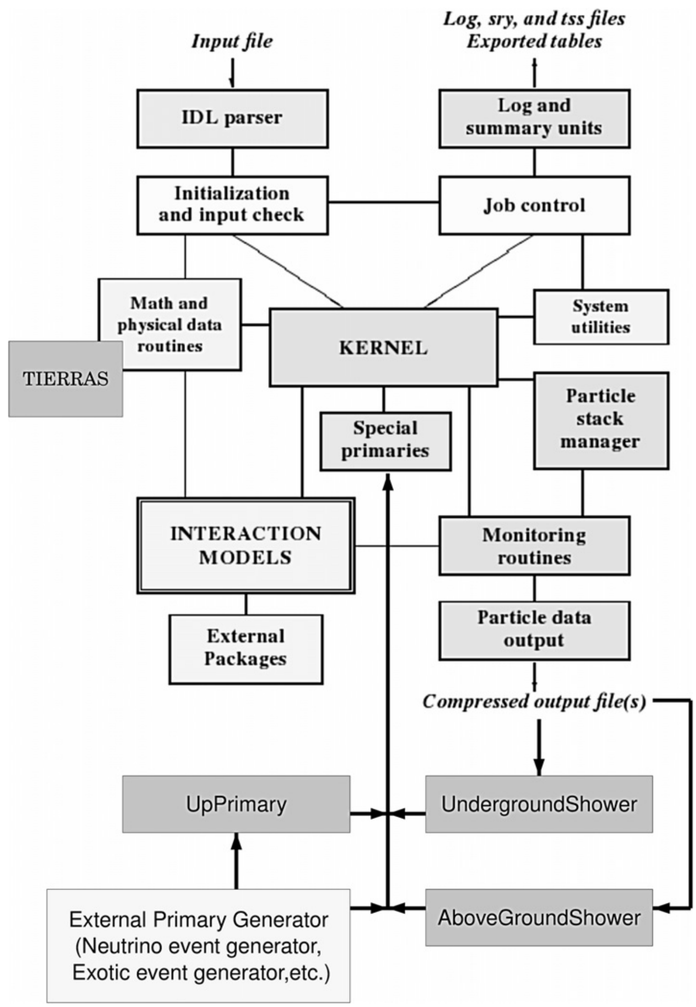


Fig. 9. The AIRES + TIERRAS program modular structure.

(b) The particle reaches ground level.
(c) A particle reaches the injection surface.
(d) A particle with quasi-horizontal motion exits the region of interest.

9. After having scanned all the stacks, it is checked whether or not there are remaining particle entries pending further processing. If the answer is positive, then all the stacks are rescanned once more; otherwise the simulation of the shower is complete.

The group of algorithms related with interaction selection and processing, as well as calculation of energy losses is the group of physical algorithms. The most important air shower observables are those related with statistical distributions of particle properties. To evaluate such quantities the simulation engine of AIRES also possesses internal monitoring procedures that constantly check and record particles reaching ground and/or passing across predetermined observing surfaces located between the ground and injection levels.

Fig. 9 contains a schematic representation of the modular structure of the main simulation programs. Every unit consists of a set of subroutines performing the tasks assigned to the corresponding unit. In general, every unit can be replaced virtually without altering the other ones. In the case of the external interaction models where complete packages developed by other groups are linked to the simulation program via a few interface routines, the modularity acquires particular importance since it makes it possible to easily switch among the various packages available.

The user controls the simulation parameters by means of input directives. After the input data is processed and checked, control is transferred to the program kernel. During the simulations the particles of the cascade are generated and processed by several packages. The interactions model package contains the physics of the problem.

The job control unit is responsible (among other tasks) of updating the internal dump file (IDF). This file contains all the relevant internal data used during the simulation, and is the key for system fault tolerant processing since it makes it possible to restart a broken simulation process from the last update of the IDF.

The kernel interacts also with other modules that generate the output data, namely, log, summary, and task summary script files, internal dump file (in either binary or ASCII (portable) format) and compressed output files generated by the monitoring routines and the particle data output unit.

In the current version of AIRES, there are two compressed output files implemented: The ground particle file and the longitudinal tracking particle file. Records within the ground particle file (longitudinal tracking file) contain data related with particles reaching ground level (passing across observing levels).

The unit named 'special primaries' consists basically in a kernel-operated interface with user-provided external modules capable of generating lists of particles that will be used to initiate a shower. This feature allows the user to start showers initiated

Table 2
Properties of the different media implemented in TIERRAS.

"Atmosphere"	4:Std soil	5:Rock [24]	6:Sosn. [26]	7:Sea water	8:Ice
ρ (g/cm^3)	1.8	2.65	2.38	1.027	0.924
Effective Z	11	11	9.54	7.435	7.435
Avg Z/A	0.5	0.5	0.499	0.553	0.553
Rad len. (g/cm^2)	27.6	27.6	30.74	36.2	36.2
Z_1	11 (33.3%)	11 (33.3%)	O (70.3 %)	O (33.04 %)	O (33.04 %)
Z_2	11 (33.3%)	11 (33.3%)	Si (24.3 %)	H (66.4 %)	H (66.4 %)
Z_3	11 (33.3%)	11 (33.3%)	Al (5.4 %)	Cl (0.56 %)	Cl (0.56 %)

by non-conventional (exotic) primary particles. This is the interface TIERRAS modules use to continue shower simulations underground, or to create up going or albedo showers.

The math and physical data routines are called from several units within the program and provide many utility calculations. In particular, they contain the atmospheric model (used to account for the varying density of the Earth's atmosphere) and the geomagnetic field auxiliary routines that can evaluate the geomagnetic field in any place around the world.

The TIERRAS core is basically a modification of the AIRES physical routines to simulate a medium with uniform density and the physical properties of an underground environment, defining a new "atmosphere" on which particles propagate. The characteristics of these new media are resumed in Table 2.

These atmospheres are defined as spherical shells with their internal radius defined as 0 m (AIRES groundlevel) and the external radius as 1400 m in rock and soil, and as 10 000 m in water and ice. The outer shell is fixed to be at 875 g/cm^2 mass depth, to make it compatible with AMIGA, but it can be easily modified for other experiments.

TIERRAS also includes external "special primaries" modules that enables its use on several scenarios:

The *UndergroundShower* module, takes the input from an AIRES compressed ground particles files (extension .grdpcles), containing the information of all the particles reaching ground level, and continues the simulation from there using a new medium in which the particles are propagated.

The *AboveGroundShower* module takes the input from an AIRES compressed longitudinal particles tracking file (extension .lgtpcles) containing the information of all particles crossing a certain level, and continues the simulation from there injecting only the particles moving in an upward direction, using a new medium in which particles are propagated. This can be used to inject up going particles from an AIRES simulation back into the atmosphere, either to study albedo effects of down going showers or up going air showers from underground initiated showers (from neutrinos, or exotic particles).

The *Uprimary* module, also part of the AIRES distribution, that enables the simulation of an up going shower, in air or underground.

The packages have several configurable parameters, like the radial cuts or particle energy cuts for accepting or discarding an input particle. These parameters are described in the documentation provided with the code, and we will skip their discussion.

These three modules can be combined to simulate a series of different physical studies, for example:

1) To study the lateral distribution of muons from a cosmic ray extensive air shower at ground level and underground:Simulate the air shower with AIRES, inject the ground level particles in TIERRAS using the *UndergroundShower* module and select the appropriate underground medium.
2) To study the albedo of cosmic ray extensive air showers: Simulate the air shower with AIRES, inject the ground level particles in TIERRAS using the *UndergroundShower* module and save the particles reaching the surface level. Inject this particles back to AIRES using the *AboveGroundShower* module.
3) Study the underground development of a particle cascade: Start a simulation of a particle of your interest, using one of the TIERRAS media. For example, start with a 1 ZeV electron (coming from strange matter decay, or a neutrino interaction) and see how much it penetrates.
4) Study the ground level signal an underground interacting neutrino: Inject the neutrino interaction secondaries using the *Uprimary* module and a TIERRAS medium. Save particles arriving to the surface.Inject them in the atmosphere using the *AboveGroundShower* module and you want to continue the simulation in the atmosphere (for fluorescence detectors, for example).

4. Installation instructions

To install TIERRAS you first need to have a working AIRES 2.8.4 installation. To get AIRES, please visit http://www.fisica.unlp.edu.ar/auger/aires/eg_AiresDownload.html. Download AIRES and its documentation. AIRES has a very good User Manual, that directly applies to TIERRAS. It is strongly suggested that you first run some simulations to get used to it. The "Learn By Examples" approach available on the doc directory is probably the best way.

Once you have installed AIRES and are familiar with it, apply the TIERRAS modification.

1) rename the files (for backup)
   To keep the original AIRES files, change the names of the following files, located on < *airesdir* >/src/aires

   atmosdata.f to atmosdata.f.ori
   atmosphere1.f to atmosphere1.f.ori
   atmosphere2.f to atmosphere2.f.ori
   ciomgr1.f to ciomgr1.f.ori
   inicheck.f to inicheck.f.ori
   modelinit.f to modelinit.f.ori
   modelutils.f to modelutils.f.ori
2) copy the files from the directory "TierrasCode" to < *airesdir* >/src/aires
3) recompile AIRES (now with TIERRAS inside!)
   from < *airesdir* >, run:
   doinstall 0

You will also need to compile, if you need to use them, the TIERRAS modules

UndergroundShower, located on the UndergroundShower Directory
AboveGroundShower, located on the AboveGroundShower Directory
Uprimary, located on the examples directory of the AIRES distribution

for this, you will do from the TIERRAS directory:

f77./UndergroundShower/UndergroundShower.c -o./UndergroundShower/UndergroundShower -L/.< *yourpath* >../aires/lib -lAires
f77./AboveGroundShower/AboveGroundShower.c -o./AbovegroundShower/AboveGroundShower -L/.< *yourpath* >../aires/lib -lAires

f77 < *airesdir* >/demos/uprimary.f -o < *airesdir* >/demos/uprimary -L/.< *yourpath* >../aires/lib -lAires

Done. You can now use Tierras

5. Test run description: The AMIGA case

We show here the results of a TIERRAS simulation for a 1 EeV shower penetrating 3 m in "Standard Soil" (proposed AMIGA design [2,27]), to illustrate the power of this new tool and some qualitative aspects of underground showers. The input files for this example are provided on the ContinueShowerPropagationUnderground directory of the Examples provided in the TIERRAS distribution.

This particular shower was simulated with a relative thinning of 10^{-5}, 0.25 weight-factor [7], and the lower energy cuts AIRES permits: 85 keV for gammas and electrons, 0.5 MeV for nucleons and mesons and 1 MeV for muons. SYBILL 2.1 was used for the hadronic model.

5.1. Longitudinal development of particles

Primary cosmic rays have their first interaction at high altitudes, and traverse many interaction lengths (typically 90 g/cm^{-2}) before reaching ground. As a result at ground level the air shower is well developed, the energy spectra of the different shower particle types are in equilibrium and passage through more air would not substantially change it.

When the shower reaches ground it encounters a sudden change in medium density, atomic number and atomic weight, triggering a sudden rearrangement of the particle energy spectrum. High energy particles encounter a much 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, the energy loss per g/cm^{-2} increases only 30% due to the medium change.

The higher back-scattering cross section also produces 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.

Fig. 10 shows an example of how all this phenomena affects the longitudinal development of the total number of particles in the shower and the total energy.

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 Fig. 10 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.

5.2. Longitudinal development of muons

Fig. 11 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 in fact secondary muons produced on the decay of other albedo particles, specially pions (see later section). 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.

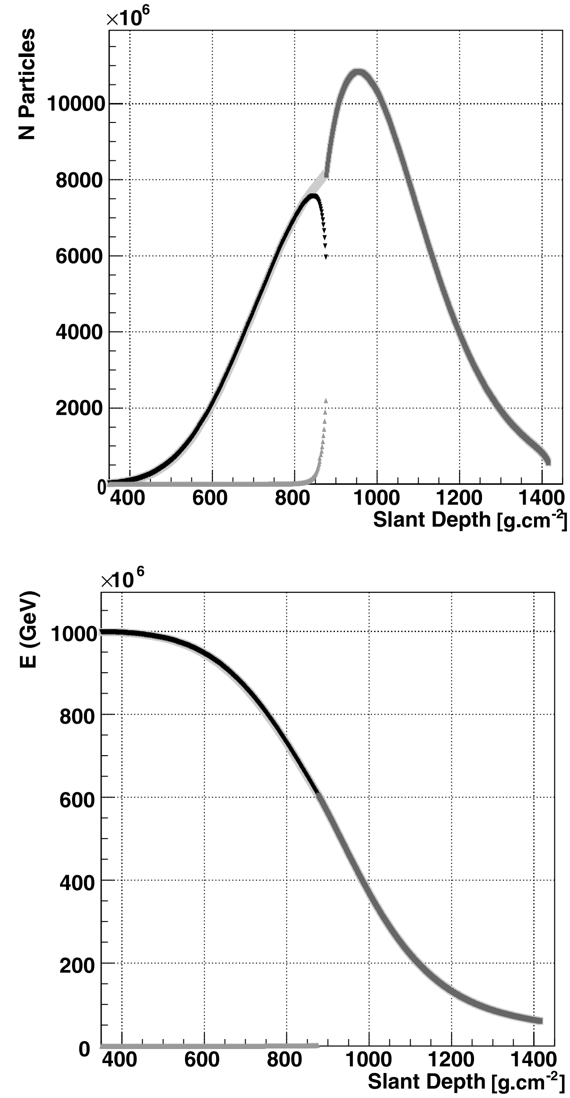


Fig. 10. Longitudinal development of all particles (top) and total energy (bottom). Black triangles correspond to AIRES simulation, dark gray squares to the TIERRAS underground simulation and light gray triangles to the Albedo component. In very light gray squares the AIRES + Albedo components are added.

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, see Fig. 12), and there is not a great transfer of energy to the muonic energy content.

The passage trough soil stops most of the electrons and low energy muons, making the mean muon energy to rise nearly 50%. The electron component of the shower is reduced nearly two decades, 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, as shown on Fig. 12.

5.3. Longitudinal development of electrons and gammas

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 total 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, as shown in Fig. 13. The development of the longitudinal profile of electrons is tightly related to the gammas profile. The electrons longitudinal profile mimics the gamma

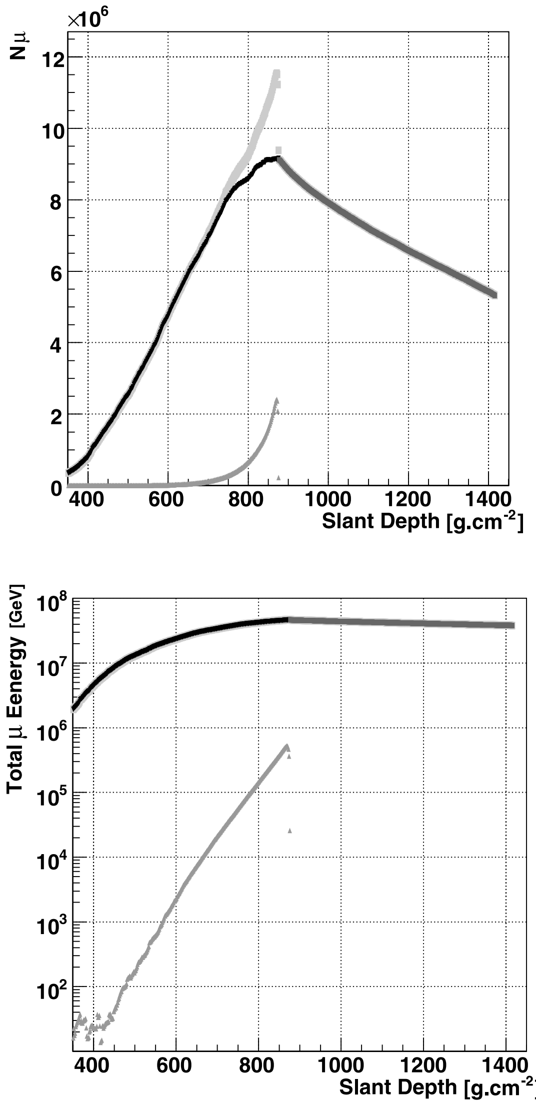


Fig. 11. Longitudinal development of number of muons (top) and muon energy (bottom). Black triangles correspond to AIRES simulation, dark gray squares to the TIERRAS underground simulation and light gray triangles to the Albedo component. In very light gray squares the AIRES + Albedo components are added.

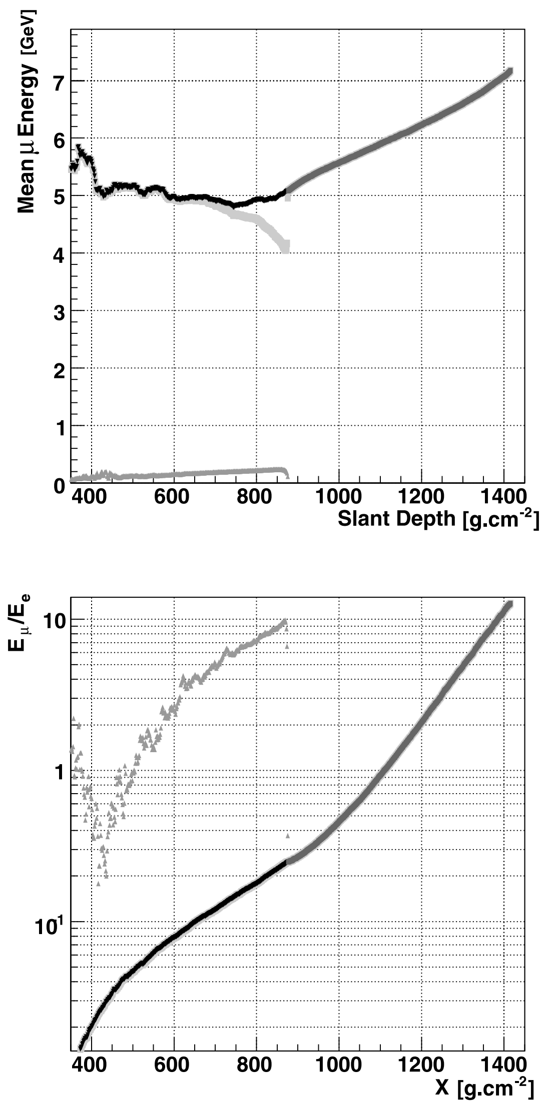


Fig. 12. Longitudinal development of the mean muon energy (top) and ratio of muon energy to electron energy (bottom). Black triangles correspond to AIRES simulation, dark gray squares to the TIERRAS underground simulation and light gray triangles to the Albedo component. In very light gray squares the AIRES + Albedo components are added.

profile, and shows the same albedo effect on the air/ground interface.

5.4. Longitudinal development of pions and neutrons

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 a 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 Fig. 14.

Pions on air decay to muons (plus neutrino) after, explaining the increase in the number of muons seen in the muon albedo (Fig. 11). Total pion energy makes a smooth transition as the one shown for the total energy in Fig. 10, showing the "redistribution" phenomena.

There is an important amount of low energy neutrons being generated below ground due to the increase in nuclear interactions, and almost half of the neutrons are produced upwards (Fig. 14). This is due to the evaporative nature of most low energy neutrons, that are generated isotropically. Up-going neutrons carry however 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, but should be taken into account in simulations of neutron monitors.

The phenomena of particle albedo has received little attention on the simulation of surface detectors signals, and many Monte Carlo codes don't track particles going upwards. Preliminary results indicate that, at least for surface water Cherenkov detectors far from the core (> 200 m), albedo particles have little contribution (1%) to the total signal. For muon or neutron counters the contribution might be higher. Further study on this topic is planned for a future publication.

5.5. Lateral densities at ground and underground

One of the most interesting observables for cosmic ray showers study in shallow underground muon detectors is the Muon Lateral Distribution Function (MLDF). The overburden provided by the soil above the detector serves to reduce the number of electron and gammas reaching the detector, as already shown in Fig. 12.

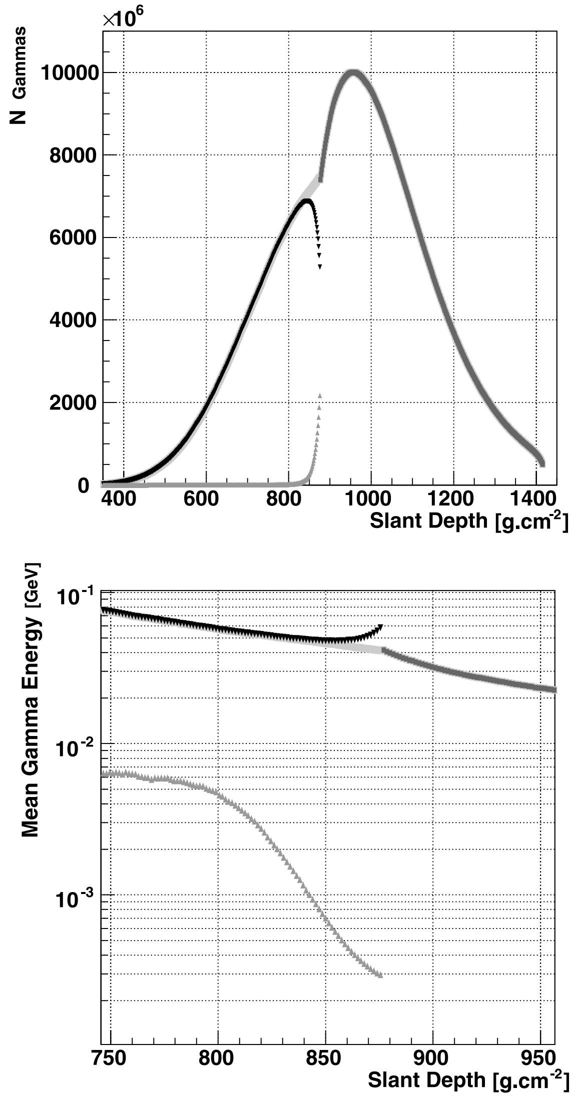


Fig. 13. Longitudinal development of Gammas (top) and Gammas mean energy (bottom). Black triangles correspond to AIRES simulation, dark gray squares to the TIERRAS underground simulation and light gray triangles to the Albedo component. In very light gray squares the AIRES + Albedo components are added.

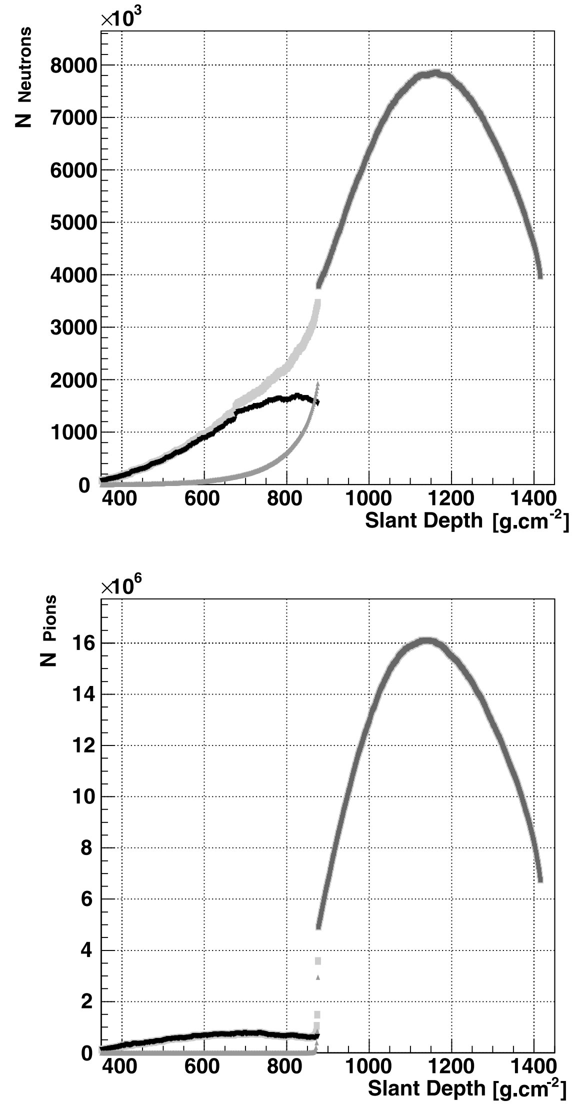


Fig. 14. Longitudinal development of neutrons (top) and pions (bottom). Black triangles correspond to AIRES simulation, dark gray squares to the TIERRAS underground simulation and light gray triangles to the Albedo component. In very light gray squares the AIRES + Albedo components are added.

Our simulations show that 3 m of Malargue Soil provide a factor 100 improvement on the N_μ/N_e ratio at 400 m from the shower core, jumping from 0.1 to 10, in agreement with the behavior displayed in the ratio of the energy components (Fig. 15). The evolution of this ratio with core distance can be seen in Fig. 16 and remains fairly constant underground, indicating that underground electrons are produced locally as muon secondaries.

In this example shower (Fig. 17) we get 0.3 μ/m^2 at 400 m from the core, in excellent agreement with previous estimations by Supanitsky et al. [28,29].

6. Conclusions

The simulation of cosmic ray showers underground using TIERRAS provides an important tool for designing, calibrating and validating underground experiments. Significantly faster than the more detailed GEANT4 or FLUKA codes, it makes it affordable to perform and improve studies that requires a large number of statistical samples like, for example, detector aperture calculations.

The original scope of this package was to continue the simulation of atmospheric cosmic ray showers some meters underground where the relevant particles are muons, electrons, gammas and maybe low energy neutrons and pions. The agreement presented in this article and many other checks that have been made but that are not presented in this work for the sake of brevity provides enough confidence for its use in shallow detector simulations.

The good agreement with experimental results for muons assures the applicability for muon content, muon lateral distribution and electron and gamma secondaries up to 1 km depth (2.5 km water equivalent). Other components still require further studies to be validated deep underground and further cross-checks with other codes and experiments are foreseen. For even 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.

The use in other experiments and configurations is being tested and will be the scope of a future publication. The potential shown in preliminary tests is encouraging and the interest and interaction with new users will surely improve it.

First results on shallow underground simulations indicate that albedo effects can be important close to the shower core and deserve more attention. The rearrangement of the particle spectrum

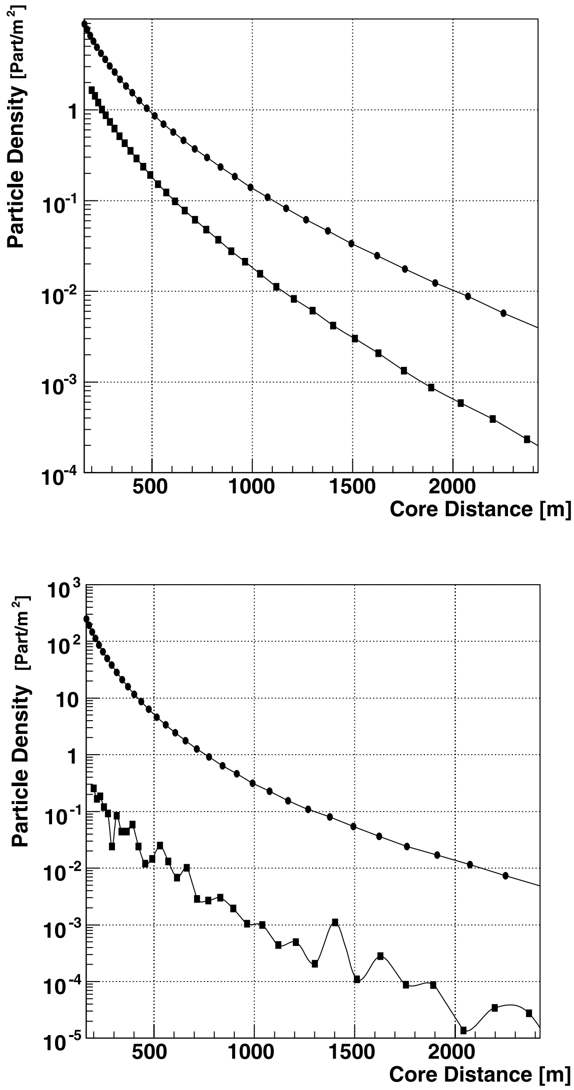


Fig. 15. Lateral density of muons (top) and electrons (bottom) at ground level (circles) and 3 m underground (squares).

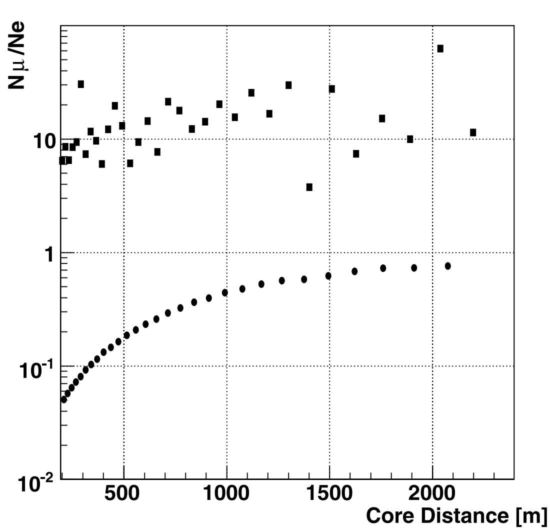


Fig. 16. Number of muons to number of electrons ratio at ground level (circles) and 3 m underground (squares) vs. shower core distance.

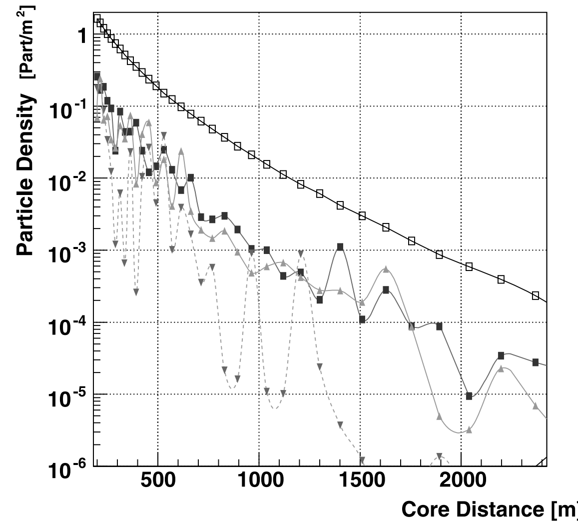


Fig. 17. Particle densities 3 m underground for a 1 EeV proton shower. Muons (open squares) are 1 order of magnitude more numerous than electrons (squares), neutrons (up triangles) and pions (down triangles).

Table 3
Elemental abundance in *El Sosneado* soil.

Element	*Z*	*A*	% (*n* atoms)
O	8	16	59.3
Si	14	28	20.47
H	1	1	8.1
Al	13	27	4.51
Na	11	23	2.63
Ca	20	40	1.68
Fe	26	56	1.34
Mg	12	24	1.2
K	19	39	0.76

in the first meters of shower development underground also indicates that detailed simulations on shallow detectors that sample particles from the "out of equilibrium" stage of the cascade are needed. This package can be used to make further studies on this subjects, and their possible impact on the detectors signal.

Acknowledgements

Part of this work was done while M.T. was visiting the Università Di Roma II Tor Vergata supported by the HELEN Program. M.T. was also supported by the Fundacion Universidad Nacional de Cuyo and CONICET. We thank A. Tamashiro, G. Rodriguez Fernandez and W. Carvalho Jr. for fruitful discussions and preliminary testing of the code.

Appendix A. Characterization of El Sosneado soil (Tables 3 and 4)

Averaging the results from the soil characterization of the *El Sosneado* area (tanks Lety and Tierra del Fuego of the AUGER surface array) [26], the following average chemical composition was obtained (% mass):

SiO_2 64.37%, Al_2O_3 12.06%, Fe_2O_3 5.62%, CaO 4.91%, Na_2O 4.27%, MgO 2.52%, K_2O 1.93%, H_2O 3.82% (derived from the humidity determinations), Other Oxides (treated as pure O) 0.4%.

Braking this down in elemental composition, using the molecular weights, gives:

Taking this information we evaluated the average Z and A taking different element combinations.

Table 4
Medium parameters for different combinations of elements in El Sosneado soil.

Elements	% of total	Avg Z	Avg A	Avg Z/A
O + Si + H	87.87	8.75	17.41	0.503
O + Si + H + Al	92.4	8.96	17.88	0.501
O + Si + H + Al + Na	95.01	9.01	18.02	0.500
O + Si + H + Al + Na + Ca + Fe + Mg + K	100	9.54	19.3	0.499
O + Si + Al	84.3	9.72	19.5	0.498

As currently AIRES uses only 3 elements to describe the medium (in air, 78% N, 21% O, 1% Ar) [7] we propose to use 70.33% O, 24.29% Si and 5.38% Al to describe *El Sosneado* soil, that gives a close match for average Z and A compared to the complete description of the samples (2% difference).

Note that this average values are lower than the 'standard soil' values of $Z = 11$ and $A = 22$, making *El Sosneado* a somewhat softer target (25% for processes scaling with Z^2).

The radiation length for this composition, calculated in accordance to the parametrizations given in [30] is 30.74 g/cm^{-2}, in comparison with the standard value given of 27.6 g/cm^{-2}.

The mean density reported is 2.38 g/cm^3 instead of the assumed 1.8 g/cm^3 in standard soil. This gives an overburden of 714 g/cm^{-2} (23 rad lengths) instead of 540 g/cm^{-2} (19 std rad lengths) for vertical particles (a 30% difference) 3 m underground.

References

[1] N. Chiba, et al., Nucl. Instrum. Methods Phys. Res. A 311 (1992) 338.
[2] M.C. Medina, et al., Nucl. Instrum. Methods Phys. Res. A 2 (2006) 302–311.
[3] The ATLAS Collaboration, ATLAS detector and physics performance, Technical Design Report, vol. 1, CERN/LHCC 99-14, 1999.
[4] MACRO Collaboration, Phys. Rev. D 52 (1995) 3793.
[5] G. Aglietta, et al., Il Nuovo Cimento C 18C (6) (1995) 629–645.
[6] R. Bernabei, et al., Il Nuovo Cimento 120B (2005) 677.
[7] S. Sciutto, AIRES 2.6 User Manual, http://www.fisica.unlp.edu.ar/auger/aires/.
[8] A.N. Cillis, et al., J. Phys. G: Nucl. Part. Phys. 26 (3) (2000) 309.
[9] P. Hansen, et al., Phys. Rev. D 71 (2005) 083012.
[10] S. Sciutto, Proc. 27th ICRC 237 (2001).
[11] A.N. Cillis, et al., Phys. Rev. D 64 (2001) 013010.
[12] R. Luna, et al., Phys. Rev. D 70 (2004) 114034.
[13] J. Knapp, et al., Astroparticle Phys. 19 (2003) 77, 99.
[14] D. Badagnani, et al., Proc. 29th ICRC (Pune) 9 (2005) 14.
[15] P. Hansen, et al., Phys. Rev. D 68 (2003) 103001.
[16] A.N. Cillis, et al., Phys. Rev. D 59 (1999) 113012.
[17] The ACoRNE Collaboration, arXiv:astro-ph/0704.1025v1, 2008.
[18] P.K. Grieder, Cosmic Rays at Earth, Elsevier Science Univ. Press, NL, 2001.
[19] D.E. Groom, Atomic Data Nucl. Data Tables 78 (2001) 183, 356.
[20] J. Formaggio, J. Martoff, Annu. Rev. Nucl. Part. Sci. 54 (2004) 361–412.
[21] T.K. Gaisser, Cosmic Rays and Particle Physics, Cambridge Univ. Press, 1990.
[22] Yu.M. Andreev, et al., Proc. 16th ICRC (Moscow) 6 (1987) 200.
[23] V.A. Kudryavstev, arXiv:0810.4635v1.
[24] D.M. Mei, A. Hime, arXiv:astro-ph/0512125v2.
[25] Y.F. Wang, A. Ferrari, et al., Phys. Rev. D 64 (2001) 013012.
[26] Segemar Isntemin, Ralizacion de estudios geologicos geotecnicos de la zona de El Sosneado, Malargue, Mendoza. Caracterizacion basica de suelos, 2007. See Appendix for details.
[27] M.C. Medina, et al., American Inst. Phys. Conf. Proc. 884 (2007) 405–410.
[28] A.D. Supanitsky, et al., American Inst. Phys. Conf. Proc. 884 (2007) 411–416.
[29] A.D. Supanitsky et al., in: Proc. of the 29th ICRC, vol. 7, 2005, p. 37.
[30] J. Linsley, in: 19th Intern. Cosmic Ray Conf., vol. 7, 1985, pp. 163–166.
[31] J. Alvarez-Muñiz, et al., Phys. Rev. D 68 (2003) 043001.
[32] M.A. Duvernois, B. Cai, D. Kleckner, in: Proceedings of the 29th ICRC, vol. 8, 2005, p. 311.
[33] T. Huege, Nucl. Instrum. Methods Phys. Res. A 604 (2009) S57–S63.