Characterization of muon simulations for the scintillator detector BATATA located at the Pierre Auger Observatory

Itzel Amayrani Martínez Salazar[a], **Dr. Gustavo Medina Tanco**[b], **Dr. Karen Salomé Caballero Mora**[a]

[a]Facultad de Ciencias en Física y Matemáticas, UNACH; [b]Institute Nuclear Sciences, UNAM

E-mail: itzel.msalazar@gmail.com

Abstract. Ultra-High energy Cosmic rays (UHECR) reach us from our Galaxy and from extragalactic space. Their origin is still unknown and their study is one of the main aims of the Pierre Auger Observatory. The underground detector Buried Array Telescope at Auger (BATATA) was designed as part of the low energy enhancement of the Observatory. This telescope is a 3 m side cube with the main goal of analyzing the muon component from air showers produced by primary Cosmic Rays (CR) and quantifying the electromagnetic contamination of the muon signal as a function of depth in the 10^{17} and 10^{18} eV energy range. The objective of this work is to characterize the functionality of simulations developed exclusively for BATATA in order to understand the behavior of the muon component in the detector. This is done by comparing the simulations with analytical calculations. In this work, results on comparisons of the muon component are presented.

1. Introduction

The Pierre Auger Observatory is located in the southern hemisphere in the province of Mendoza, Argentina with an area of 3000 km^2. It uses two types of detectors, fluorescence telescopes and water-Cherenkov stations, therefore it is a hybrid detector, which aims to determine the nature, energy and origin of cosmic rays with energies over 10^{17} eV (See Figure 1). The Surface Detector (SD) consists of an array of 1660 water-Cherenkov detectors separated by 1.5 km, each station is independent with 3.6 m in diameter, 1.2 m depth and a capacity of 12 tons of pure water. The Observatory has 24 Fluorescence Detectors (FD) distributed in 4 buildings. These detectors operate at night when there is little background light so that they only detect the light emitted by the cascade in the atmosphere [1]. In recent years, the Pierre Auger Collaboration decided to expand the detection range to observe cosmic rays of lower energy (up to 10^{17} eV). The enhancements include fluorescence telescopes at high elevation (HEAT), underground muon detectors (AMIGA and BATATA) and detectors for radio (AERA) and microwave emissions of atmospheric showers. As part of the upgrade called AugerPrime, additional muon detectors are being depoyed in the original SD [2].

1.1. Description of the detector BATATA

Buried Array Telescope at Auger (BATATA) is an additional prototype for the AMIGA counter [3]. It was designed as part of the low energy enhancement of the Observatory, with the main aim of analysing the muon component from air showers produced by primary CRs and quantifying the electromagnetic contamination of the muon signal as a function of depth in the 10^{17} and 10^{18} eV energy range. This telescope is a 3 m side cube installed underground. It consists of six layers of plastic scintillator, buried at a depth between 30 cm and 2.5 m (See Figure 2). Each layer in a plane is 4 m^2 and composed by 50 rectangular bars of 4 cm x 2m, oriented at a right angle whith respect to its companion layer, which gives an xy-coincidence of 4x4 cm^2 [3] and [4]. BATATA is an independent detector, which can be used to perform studies of the interactions taking place in the air shower through the muonic component.

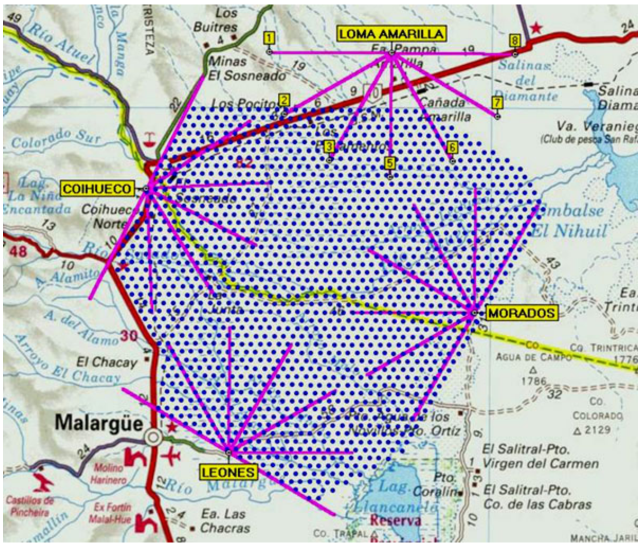


Figure 1. Area of the Pierre Auger Observatory in Mendoza, Argentina. Blue dots are SD stations. The four FD sites are shown in yellow.

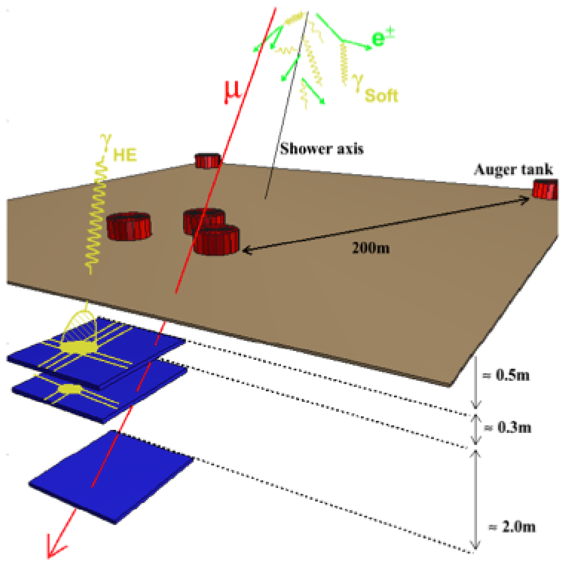


Figure 2. BATATA structure (see text).

2. Simulations

A code exclusive for BATATA has been developed at UNAM [5], based on python. This code, called in this document *cascade*, aims to describe the detection probability of muons and electrons at the detector based on analytical calculations taking into account the propagation of such particles through BATATA. It is important to mention that another simulation code has also been developed for BATATA, based on the Geant4 tool, to monitor the soil particles in *Malargüe* observatory region, see [3] and [4], this is not used in this work.

2.1. Analytical calculation of the detection probability

Analytical calculations were developed by Dr. Gustavo Medina Tanco from the Institute Nuclear Sciences, UNAM (private communication). Those calculations describe the detection probability of muon and electromagnetic components, based on the propagation of such particles through the detector. These calculations can be obtained for a given particle with different initial conditions using the software **Mathcad** (version 14.0). For more information on these calculations please see Appendix A in [6].

2.2. Description of "cascade" code
The code provides a simulation of muonic and electronic components from low energy particle interactions in the atmosphere. It is possible to throw muons and electrons of different energies and different geometries through the detector for pattern recognition based on statistics. The spread of particles arriving to the detector is represented, in the simulation, by the intersection of a cylinder with the layers which form the detector. That intersection has the shape of an ellipse as shown in Figure 3.

The *cascade* code is handled with two general scripts: **escritura.py** and **mezcla**, which work as follows:

escritura.py: is a code for writing data configuration parameters.

mezcla: is the master script, it runs once you have configured the escritura.py code from a terminal such as: ./mezcla.

3. Description of the method

The goal is to verify that the *cascade* code behaves correctly in comparison to the analytical calculation of detection probability. To perform the study, a certain number of particles are thrown on the detector with a vertical zenith angle ($\theta = 0°$), for an energy of E= 114 MeV. The election of the energy is arbitrary but is of the order of particles expected to be detected by BATATA. For comparing the detection probability, the efficiency, i. e., the ratio of the number of particles reaching the detector and the total number of particles thrown, is considered as the probability.

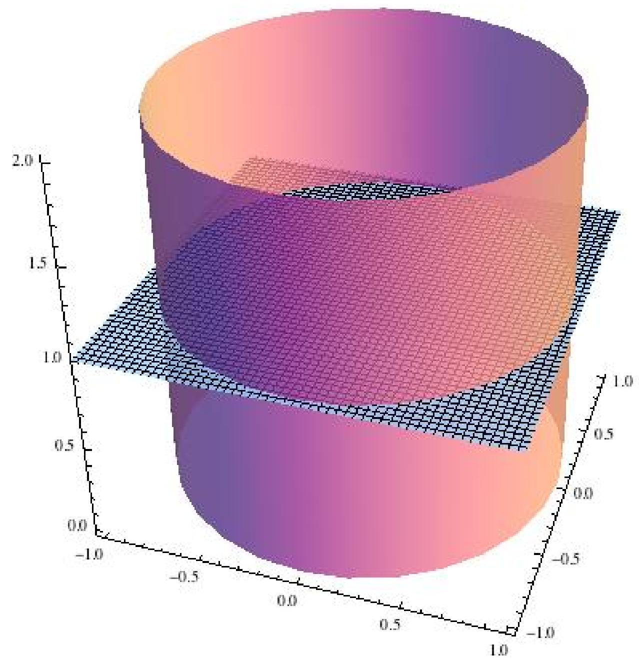
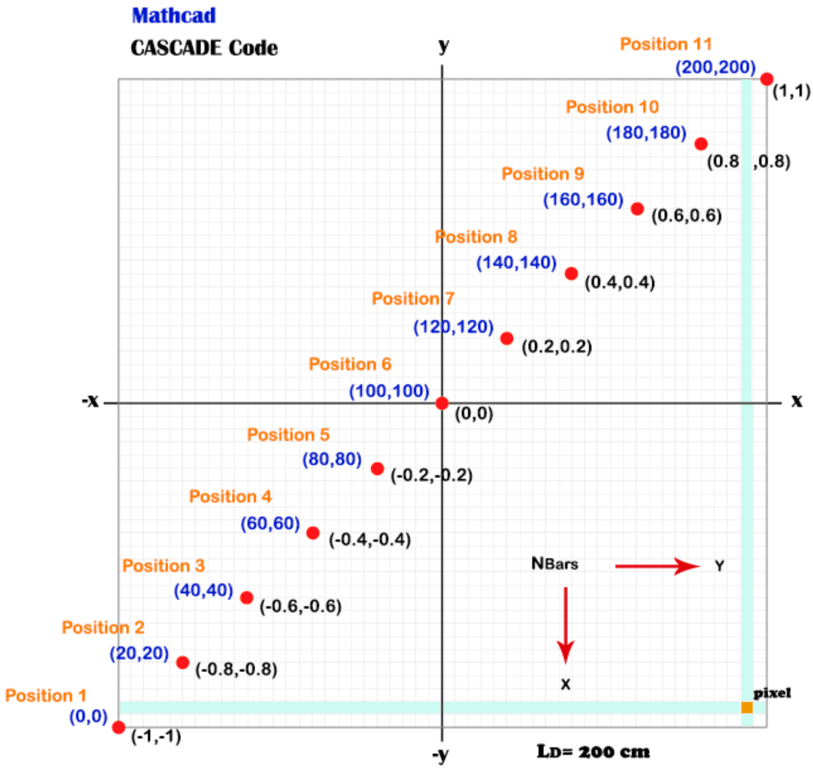


Figure 3. Schema of the shape used to describe particles reaching the detector, as used in the *cascade* code.

3.1. Equivalence of positions
For comparing the positions of the two codes (*cascade* and the analytical calculation) we should take into account the general characteristics of the detector. Figure 4 shows 11 positions along a diagonal of the detector, wich are considered as locations to throw the particles on, for a first study. These particles represent the detected particles.



- N_{Bars}= 50
- x-Direction: i:1,2...N_{Bars}
- y-Direction: j:1,2...N_{Bars}
- Lateral side of the detector: L_D : 200 cm
- Pixel size: $\frac{L_D}{N_{bars}}$

Figure 4. Equivalence of the 11 positions in Mathcad and *cascade*. Blue points correspond to the location according to Mathcad coordinates and black points correspond to the *cascade's* ones.

3.2. Efficiency calculation
Cascade efficiency corresponds to the detection probability in BATATA, calculated in Mathcad.

Three cases are analyzed:

(a) 25,000 particles with $0° \leq \theta \leq 36°$, E= 114 MeV, $0° \leq \phi \leq 36°$ for each position of the diagonal were thrown (See Figure 5).

(b) From the 25,000 particles thrown in (a), only 1000 with theta between 6° and 21° are chosen. This is done for approaching as much as possible a vertical position, close to zero, according to the possibilities of the code. The efficiency is calculated for those particles.

(c) With the aim of obtaining a more accurate comparison, as is done for the analytical calculations (for **Mathcad** the angles considered are fixed values not ranges as in *cascade*), the range of angles is reduced to $3° \leq \theta \leq 9°$ and $33° \leq \phi \leq 39°$ (See Figure 5).

4. Results

4.1. Muon component

Figure 5 shows that the best option to check the compatibility between cascade and the analytical calculation is (c). The differences between the analytical calculations and simulations are in most of the locations, below 10%.

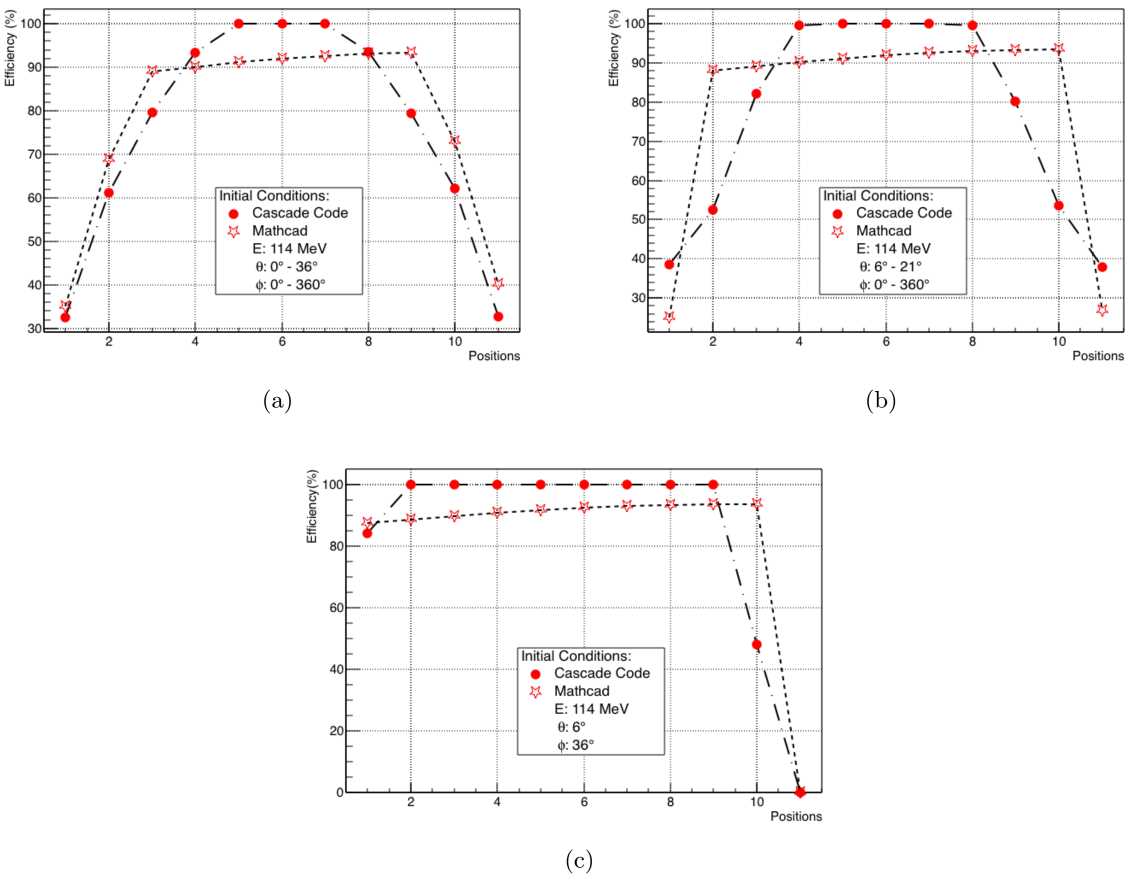
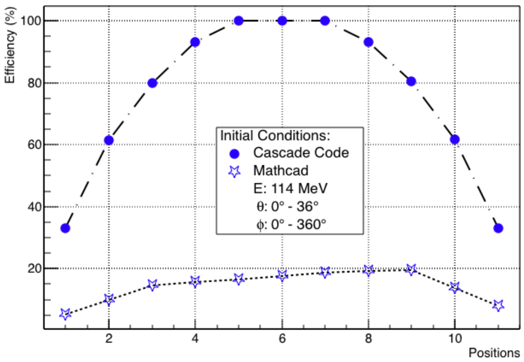


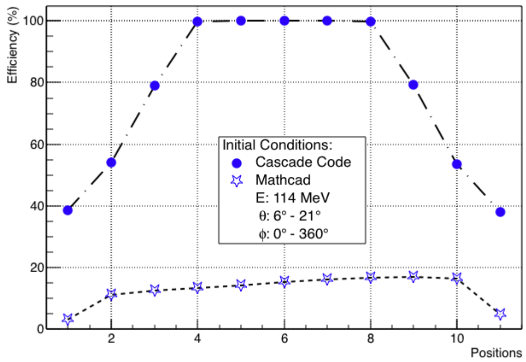
Figure 5. Comparison of compatibility between the code *cascade* and the analytical calculation described in Mathcad for the muon component.

4.2. Electromagnetic component

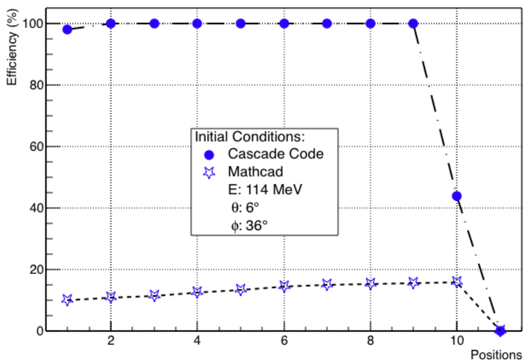
The results are shown in Figure 6. From these Figures it can be seen that *cascade* does not reproduce the analytical calculations for the electromagnetic component. It has been found out that *cascade* code does not includes the corresponding propagation equations for the electromagnetic component.



(a)



(b)



(c)

Figure 6. Comparison of compatibility between the code *cascade* and the analytical calculation described in Mathcad for the electromagnetic component.

5. Conclusions

The code *cascade* developed for describing measurements done by BATATA has been tested. The best initial conditions to use it for reproducing analytical calculations of efficiency for vertical zenith angles are found. At the moment *cascade* works properly for the muon component, however it can be adapted to include the code corresponding to the electromagnetic one.

6. Acknowledgments

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[5] The authors of this code are: Leonardo A. Castro Institute of Physics, Department of Theoretical Physics, UNAM; Jorge D. Brown of the Institute Nuclear Sciences, department of high energy physics, and Enrique Escalante, Institute of Physics, Department of Theoretical Physics, UNAM.

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