Monte Carlo Simulation for Background Noise Study of the Wudalianchi Volcano with Cosmic Ray Muons

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Abstract

Muon radiography has become a powerful tool to study the volume density of large objects of a few hundred meters scale. However, background noise can reduce significantly the efficiency of this technique if not adequately eliminated. In our muon radiography experiment to image the density structure of the Wudalianchi volcano in northeast China, the muon flux was overestimated due to background noise leading to a serious underestimation of the volcano density. To estimate correctly the level of background noise and propose solutions to reduce it, we use the CRY (cosmic ray shower library) library to generate the cosmic particles (electrons, protons, and muons) and the GEANT4 tool to simulate the interaction of cosmic muons within the volcano structure. The results show that the background noise in muon radiography is mainly made of low-energy particles (less than 2 GeV). To discriminate this background and eliminate it, we study the feasibility of two methods: one is based on using absorbers in front and between the detection layers to stop low-energy particles or to increase their angular deviation, so they can be efficiently tagged. The second is based on the Time of Flight (ToF) technique. The two methods aim at separating low- from high-energy particles. This study will be instructive for our next volcano experiments.

Keywords: muon radiography, background noise, volcano, ToF, absorber
DOI: 10.31526/JAIS.2022.274

1. INTRODUCTION

The Wudalianchi volcano is located in Heilongjiang Province, China. The last eruption occurred about 300 years ago. It is the youngest active volcano in China. From September 23 to November 10, 2019, we conducted a one-month observation of the Wudalianchi Laoheishan volcanic cone. The device used in this experiment was a tracking detector made of plastic scintillator bars read out using SiPM technology. Aerial photography was previously obtained by a dedicated drone to reach high-resolution topographic data of the volcano (Figure 1). More than 3 million valid trajectory particles were collected during this observation.

Due to background noise, the muon flux ratio[1] of muons coming from the volcano side and that of those from the opposite one (open-sky) were, however, found to be about one order of magnitude larger than expected. Similar results were already found by Ambrosino et al. [1] with two different detection techniques. The main source of this increase was found by Nishiyama et al. [2] to be low-energy particles. These low-energy particles fake our density estimate and need thus to be eliminated.

In this work, we perform a detailed Monte Carlo simulation to obtain the expected numbers of electrons, protons, and muons and their energy spectra in our detector at the Wudalianchi site. Then, we use absorbers and Time of Flight (ToF) techniques to extract background noise. The combination of these two techniques allows us to eliminate almost all the low-energy particles while retaining most of the high-energy muons. This paper is divided into three main parts. (1) First, we evaluate the energy of the different particles present in the muon radiography using CRY and GEANT4 simulation tools. (2) We give then the proposed method of background noise subtraction. (3) We finally present the results of our study in a few realistic detection scenarios.

2. ENERGY SPECTRUM OF BACKGROUND NOISE FROM SIMULATION

In this work, we use CRY code [3] to simulate both cosmic muons as well as background noise. CRY is a software library for generating distribution of cosmic shower particles. It does not need to trace the particles from their origin, which makes it a fast

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[1] All flux ratios in this paper refer to the ratio between the flux in the volcano scenario and that in the Open-sky scenario.

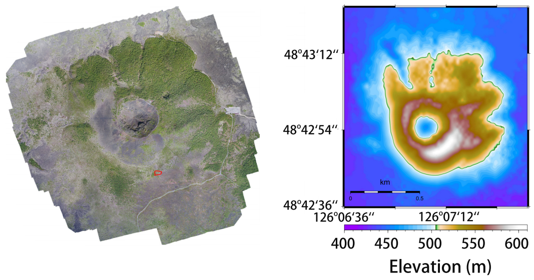

FIGURE 1: (Left) High-resolution topography from aerial photogrammetry by drone. (Right) Elevation map of the Laoheishan volcano.

and convenient tool. The use of CRY to generate the cosmic particles was then followed by using GEANT4 to simulate the loss of energy of cosmic muons in the volcano structure before that they cross to reach our detectors.

We collect the energy and direction of the electrons, protons, and muons within the zenith angular range $\Delta\theta_1$ from 65° to 85° corresponding to the angle under which the volcano is seen by the detector. The azimuth angle range $\Delta\theta_2$ is a 180° opening angle facing the mount from the detector. Then, we can deduce the particle energy spectrum under the Open-sky scenario (Figure 2(left)). It can be seen that the contributions of electrons and protons are mainly concentrated in the low-energy region (less than 2 GeV). This is consistent with the study of Nishiyama et al. [2]. And we can also see more research on the background energy spectrum of volcanoes in [4, 5]. Exploiting the minimum energy loss information of CSDA (Continuously Slowing Down Ability) with a rock average density of ($\rho = 1.7\,\mathrm{g{\cdot}cm^{-3}}$) and the Wudalianchi volcanic topography, the energy spectrum of muons passing through the volcano can be deduced as can be shown in red in Figure 2(right).

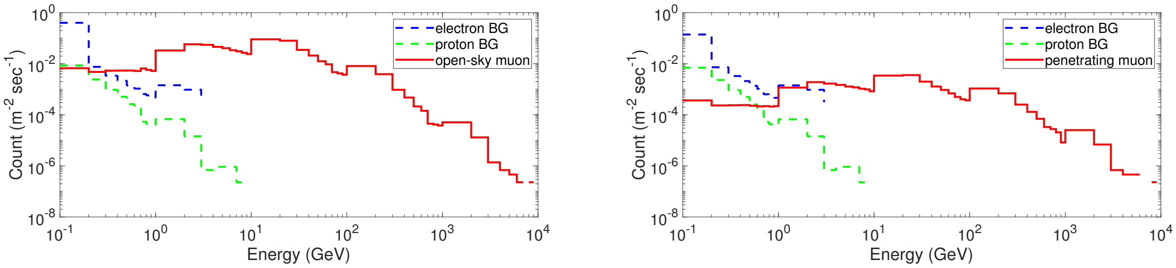

FIGURE 2: Left: The particle energy spectrum under the Open-sky scenario. Right: The energy spectrum of muons passing through the volcano. The results are basically consistent with those shown in [2].

According to the particle energy spectrum obtained from the simulation, we can deduce the ratio of penetrating muons in the volcano scenario to muons in the Open-sky scenario (Figure 3(left)) and also the particle $(\mu + e + p)$ flux ratio between the volcano scenario and the Open-sky scenario (Figure 3(right)).

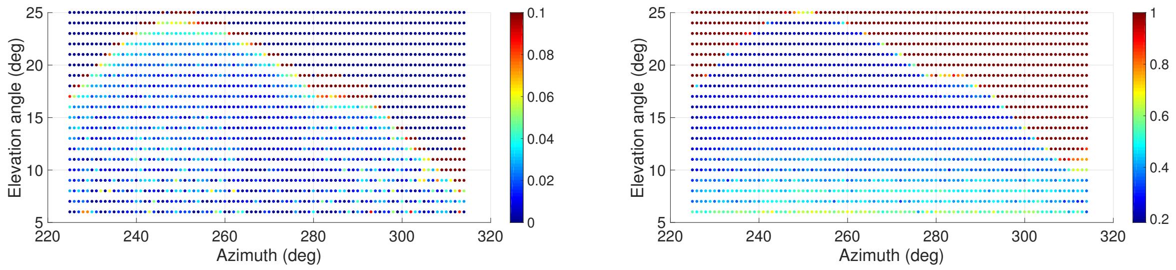

FIGURE 3: (Left) The ratio of penetrating muons in the volcano scenario to muons in the Open-sky scenario. (Right) The particle $(\mu + e + p)$ flux ratio between the volcano scenario and the Open-sky scenario.

Figure 3 shows that when we consider the effects of electrons and protons, the particle $(\mu + e + p)$ flux ratio within the azimuthal range of the volcano is about one order of magnitude larger than if we only consider muons. This shows once again from the simulation that the background noise in the volcano experiment mainly comes from low-energy electrons and protons.

To get rid as much as possible of this background noise, a new experiment equipped with detectors able to discriminate the low-energy particles and eliminate them is needed. To achieve this, we study in detail the subtraction method of low-energy background noise using a combination of high position resolution detectors such as RPC (Resistive Plate Chamber), high time resolution detectors like the MRPC (Multigap Resistive Plate Chamber), and absorbers, and then, we give an optimized setup to be used in a future muon radiography experiment.

3. BACKGROUND NOISE SUBTRACTION

As mentioned earlier, the background noise in volcano muon radiography is mainly composed of low-energy particles. In order to distinguish and eliminate background noise, we study two methods: one is to use absorbers to either stop low-energy particles or to increase their angle deviation, so thanks to detectors with high position resolution, one can identify them. The other method is to distinguish low- and high-energy particles based on the ToF provided by fast time detectors. The two methods can be combined as shown in one setup in Figure 4 that is successively made, starting from the volcano side, of 2 cm iron plate, one MRPC, four layers of GRPC each with 4 mm aluminum plate brackets, and finally another MRPC. We have studied several scenarios by changing the whole length of the device. Two scenarios of 1 m and 2 m spacing will be presented hereafter.

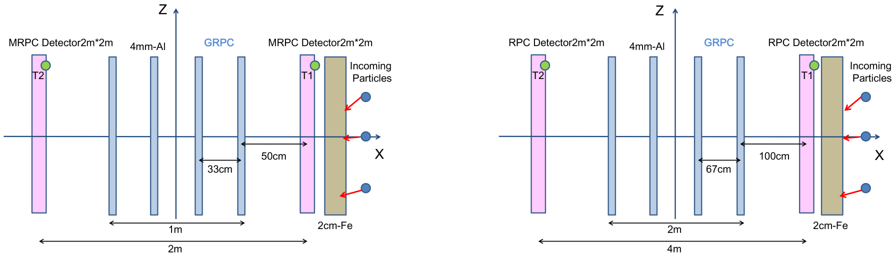

FIGURE 4: (Left) MRPC spacing is 1 m. (Right) MRPC spacing is 2 m.

3.1. *Absorbers and Angle Deviation*

First, we use absorbers and the angle deviation of particles crossing the setup to eliminate background noise. As can be shown in Figure 4, the 2 cm iron plate and the 4 mm aluminum plates are used to stop very low-energy electrons and protons. To identify the other low-energy particles, we measure the zenith angle ($\Delta\alpha$) and the azimuth angle ($\Delta\beta$) of the particle using the particle track coordinates recorded by the different detectors:

$$\Delta\alpha = \frac{Y2 - Y1}{X2 - X1}, \qquad \Delta\beta = \frac{Z2 - Z1}{X2 - X1}, \tag{1}$$

where $\Delta\alpha$ is the zenith angle of the line connecting the front and rear point coordinates of the particle track and $\Delta\beta$ is the azimuth angle of the same line. We then choose an appropriate angle for particle elimination depending on the detector spatial resolution. For example, when the position resolution of the detector is 5 cm and that of the two MRPC spacing scenarios is 1 m, the angle deviation cut is taken as 2° and we remove the particles whose $\Delta\alpha$ or $\Delta\beta$ is found to be greater than 2° when the particle passes through all the detectors. This selection eliminates most of the electrons and protons.

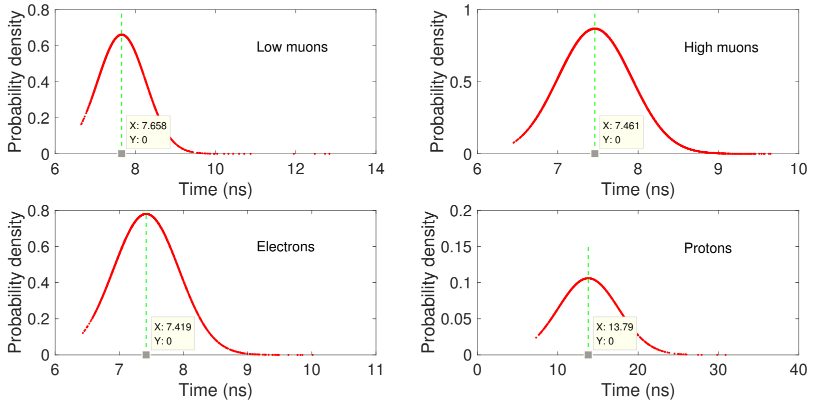

FIGURE 5: The ToF distributions of high muons, low muons, electrons, and protons in the case of the 2 m detector spacing.

3.2. *ToF*

Secondly, we use the ToF to distinguish low- from high-energy particles. Figure 5 shows the ToF distribution of muons below 2 GeV, and muons above 2 GeV as well as those of electrons and protons in the case of the 2 m spacing scenario.

Using the significance formula $\sigma = \frac{S}{\sqrt{S+B}}$ (S represents the number of muons retained under a certain time cut selection, B represents the number of electrons and protons retained with the same selection), we can get the best time cut ($T_{\mathrm{cut}} = 9.615\,\mathrm{ns}$ in the case of 2 m spacing). In this way, the low-energy particles with ToF greater than 9.615 ns will be removed while keeping particles with a shorter ToF. The time resolution of MRPC is taken as 100 ps which is rather achievable based on the current performances of such a detector.

3.3. Subtraction Results

Using the above series of devices and methods to separate low- from high-energy particles, we finally get the background noise elimination results in Table 1. The following can be seen. (1) An iron plate of only 2 cm can absorb about 90% of electrons and about 65% of protons. (2) About 50% of low-energy electrons can be removed by using the angle deviation of the particle track. (3) Using the ToF can remove most of the protons. In the end, we use the above-mentioned series of devices and methods to remove almost all low-energy particles, while retaining almost all high-energy muons.

Detector spacing = 1 m	High-energy muons	Low-energy muons	Electrons	Protons
Incoming particles	100%	100%	100%	100%
2 cm iron	100%	96.8%	11.1%	35.5%
Last detector	99.9%	94.8%	6.7%	26.0%
Angle deviation	99.9%	94.2%	3.3%	24.9%
Time cut	99.8%	93.1%	3.3%	3.1%

Detector spacing = 2 m	High-energy muons	Low-energy muons	Electrons	Protons
Incoming particles	100%	100%	100%	100%
2 cm iron	100%	97.1%	11.1%	35.4%
Last detector	99.8%	92.0%	5.5%	24.3%
Angle deviation	99.8%	91.6%	3.0%	23.5%
Time cut	99.8%	90.5%	3.0%	2.2%

TABLE 1: Background noise subtraction results.

In the literature on the rejection of volcanic background [5, 6, 7, 8], the Muon Telescope (MuTe) is used to recognize muography background sources such as upward coming muons, scattered muons, the soft component of Extensive Air Showers (EAS), and simultaneous arriving particles. They are filtered by measuring deposition energy and ToF. These studies are very detailed in the classification of background noise. But the background particles simulated in this paper are generated by simplified scenes. It can be seen from Table 1 that the elimination of low-energy muons has not been completed, which is caused by the too rough division of low- and high-energy muons in our simulation. As a future work of muography, we will simulate real volcanoes interacting with cosmic rays in GEANT4 and use neural network technology to better eliminate muography background noise.

4. CONCLUSION

In this paper, we analyze the results of muon radiography experiment data of the Wudalianchi volcano, and simulated the background noise of the volcano by using CRY and GEANT4 software tools. We found that the background noise in the volcano experiment mainly comes from low-energy particles. We then studied two methods, absorbers-based and ToF, to eliminate this background noise. We finally used a combination of the two methods to remove almost all low-energy particles while retaining most of the high-energy muons. The result of this study allows us to envisage the use of such a scenario n future muon radiography experiments.

CONFLICTS OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] F. Ambrosino, A. Anastasio, A. Bross et al., Journal of Geophysical Research: Solid Earth **120**, 7290–7307 (2015).
[2] R. Nishiyama, A. Taketa, S. Miyamoto, and K. Kasahara, Geophysical Journal International **206**, 1039–1050 (2016).
[3] C. Hagmann, D. Lange, D. Wright, 2007 IEEE Nuclear Science Symposium Conference Record **2**, 1143–1146 (2007).
[4] A. Vesga-Ramírez, D. Sierra-Porta et al., Muon Tomography sites for Colombian volcanoes[J]. arXiv preprint arXiv:1705.09884, 2017.
[5] J. Peña-Rodríguez et al., Muography background sources: simulation, characterization, and machine-learning rejection[J]. 2021.
[6] J. Marteau, J. D'ars, D. Gibert et al., Implementation of sub-nanoseconds TDC in FPGA: applications to time-of-flight analysis in muon radiography[J]. arXiv preprint arXiv:1310.4281, 2013.

[7] K. Jourde, D. Gibert et al., Effects of upward-going cosmic muons on density radiography of volcanoes[J]. arXiv preprint arXiv:1307.6758, 2013.

[8] J. Peña-Rodríguez, L. A. Núñez, and H. Asorey, Characterization of the muography background using the Muon Telescope (MuTe)[J]. arXiv preprint arXiv:2102.11483, 2021.