Algorithm for muon path reconstruction in a large area muon detector

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Abstract

Muon detection is essential for gamma ray astronomy. It can be achieved by using large area muon detectors. They enable us to obtain the number of muons passing through the detector area during a particular cosmic ray shower. The direction of the cosmic ray shower also reveals a lot of information. This program uses the data generated by a large area muon detector and reconstructs the most probable paths of the detected muons. The output is generated in the form of angles of the reconstructed tracks, the detector numbers through which the tracks pass and a diagrammatic representation of the reconstructed tracks can also be obtained.
The program is developed for the large area muon detectors employed at the GRAPES-3 experiment located at Ooty, India.

1. Introduction

The GRAPES-3 (**G**amma **R**ay **A**stronomy **P**eV **E**nergie**S** phase – **3**) experiment aims to probe acceleration of cosmic rays in various astrophysical settings. The experiment is set up at Ooty, India (N11.4°, E76.7°, 2200m above mean sea level) and is supported by a collaboration of various institutes from India and Japan.
The experiment consists of an array of scintillator detectors and four stations of large area muon detectors. The scintillator detectors are used to detect charged particles produced by the interaction of high energy cosmic rays in the atmosphere. The muon detectors are used for purely detecting the muons incident in a cosmic ray air shower. Threshold energy for the large area muon detectors is 1 GeV. Each of the stations consists of four modules. These modules consist of proportional counters.
Proportional counter (PRC) is the basic element of the GRAPES-3 muon detector. The PRC is a 600 cm long, mild-steel, square pipe with a cross-sectional area of 10 cm 10 cm and a wall thickness of 2.3 mm. A muon detector module with a sensitive area of 35 m^2 consists of a total

Fig. 1. A picture of the location of the GRAPES-3 experiment. The small aluminium conical structures are scintillator detectors.

of 232 PRCs arranged in 4 layers (58 PRCs in each layer), with alternate layers placed in orthogonal directions. Two successive layers of PRCs are separated by 15 cm thick concrete, consisting of 60 cm X 60 cm X 15 cm blocks which permits a two-dimensional reconstruction of muon tracks in two vertical, orthogonal planes. The vertical separation of two layers of PRCs in the same plane is 50 cm.

To achieve an energy threshold of 1 GeV for vertical muons, a total thickness 550 gcm^2 in the form of concrete blocks is employed as an absorber by placing a total of 15 layers of concrete blocks above Layer-1.

During a cosmic ray shower, muons are detected by the PRCs of each of the four layers. The in-house developed DAQ system records all the data generated by the large area muon detector. It stores the total number of PRCs which detected muon(s) in each layer. It is also able to identify the counters from each layer which detected muon(s) and also those which did not. This data is stored in the form of a text (.txt) file.

With this program, it is possible to reconstruct the possible tracks of the detected muons with a considerably good accuracy by using the available data. Reconstructed tracks can be used to obtain the angular direction of the detected muons and also to find the PRC numbers through which they passed.

The reconstructed tracks can be obtained only between each set of parallel placed detector layers (viz layer 0 – layer 2 and layer 1 – layer 3) since consecutive layers are mutually orthogonal. But, using the individual data of both the sets of layers, the spatial angles of the cosmic ray shower can be determined.

Each reconstructed path is obtained by considering all possible paths of the detected muons and then finding the ones which have the maximum probability of being the muon path.

In order to test, verify and find the efficiency of this program, simulated data is used and actual known angles of muons are compared with the reconstructed angles.

Fig. 2. An inside view of a super-module showing the proportional counters and layers of concrete blocks for two of the four modules.

2. Development Framework

The program is developed in the ROOT scientific data analysis framework and uses its libraries and methods for execution. The ROOT framework is developed at CERN, majorly for high energy physics experiments. It is mainly based on C++ environment.

3. Simulations

The entire development and testing of the program has been performed using simulated cosmic rays in Earth's atmosphere from CORSIKA. CORSIKA (Cosmic Ray Simulation for KASCADE) is a standard extensive air shower simulation code. It allows interaction and decay of particles in atmosphere up to energy 10 20 eV and give type, energy, location, direction and arrival times of all secondary particles from the interactions.

CORSIKA 74001 was used to simulate the extensive air showers (EAS). The FLUKA model was chosen for low energy hadronic interaction (< 80GeV) while the SIBYLL model was used for high energy hadronic interactions. The energy cut (Ecut) for muon was fixed to 1GeV, corresponding to the energy threshold of the large area muon detectors of GRAPES-3.

The simulated showers are used to trigger the PRCs in the detectors and muon paths are reconstructed. But, since this is a simulated shower, the actual paths of muons are already known and hence can be used to compare with the reconstructed path and determine the efficiency of the program.

All the PRCs in each layer are numbered from 0 to 57 and hence can be identified accordingly. Whenever a muon from this simulated shower passes through a PRC, a flag is raised to indicate the same. An array of all such PRCs is stored and then passed on to the algorithm to reconstruct the possible tracks.

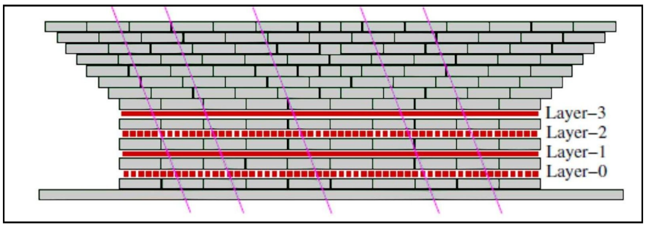


Fig. 3. A diagrammatic representation of a single module of the large area muon detector. The grey layers indicate the concrete blocks while the PRC layers are represented in red. The purple tracks represent the incident muon particles from a cosmic ray extensive air shower.

4. Algorithm

The algorithm is same for both the sets of layers (layer 0-layer 2 and layer 1-layer 3) but runs independently for both. For further discussion, layer 0-layer 2 set is considered.
The reconstruction algorithm works in two parts. The first part uses the difference between the PRC numbers as its basis while the second part relies on the angle made by the possible tracks and comparing them.

Part 1:
It runs in an iterative manner.

1. Firstly, a counter which has recorded muon(s) from layer 2 is selected. Let its PRC number be *t*.
2. All possible paths from this PRC are found out by considering paths starting from it and going to all of the muon detecting counters in layer 0. Let the PRC number of a PRC in layer 0 be *y*.
3. For each of the possible paths, the quantity *t-y* is calculated and stored.
4. This process is repeated iteratively for all the muon detecting PRCs from layer 2.
5. Then, the number of occurrences of *t-y* values are found out. The value which occurs the most number of times is considered as the most probable reconstruction path.
6. If two values occur the most number of times, the lower value is given preference.
7. Depending on the quantity, *t-y*, the allowance range of either one or two PRCs for each possible path is determined.
8. For the boxes with two PRC allowance range, the path with lesser deviation from *t-y* is given preference.
9. In order to account for the case where a single muon passes through two counters, for every possible path, its adjacent counters are checked if they indicate a muon hit but have not been associated with a possible reconstruction path. In this case, the reconstructed path is determined through both the counters.

Part 2:

1. For each of the muon detecting PRC in layer 2, all possible paths are constructed by considering paths starting from it and ending at each of the muon detecting PRCs in layer 0. But these paths are considered only for those PRCs in layer 0 which have *t-y*>-8 and *t-y*<8. Angles of all such paths are recorded.
2. For a particular muon detecting PRC in layer 2, the angles of all possible paths are

compared with the angles of all possible paths of all the remaining muon detecting PRCs in layer 2. Every time the angles are 'matched', the probabilistic weight for that angle (or path) is increased.

3. Step 2 is repeated for all muon detecting PRCs in layer 2.
4. For each of the muon detecting PRC in layer 2, the path which has the maximum probabilistic weight is considered as the reconstructed path for the muon passing through it.
5. The process of 'matching' the angles is done by calculating the angular resolution for the detector and therefore varies dynamically for all PRCs. Suppose the angle of incidence is α, the compared angle should lie within $\alpha - \delta\ \alpha$ and $\alpha + \delta\ \alpha$ for them to be matched.

The quantity is the allowance which is dependent upon the angular resolution of the detector.

$$\delta\alpha = \frac{R^2 w - d^2}{R^3 cos(\alpha)}$$

Here,
w is the width of each counter.
d is the quantity *t-y.*
R is the total distance (hypotenuse) from the PRC in layer 2 to PRC in layer 0.

The reconstructed paths determined via both the parts are combined together in order to create a better reconstruction. The final reconstructed muon tracks are then passed to the required output function.

5. Assumptions and approximations

The program has been developed for the large area muon detectors of the GRAPES-3 experiment. Considering the detector geometry and the observed data over the period of several decades, a few assumptions and approximations have been made while trying to reconstruct the muon path.

1. All muons from a single cosmic ray shower are almost parallel and their directions don't vary by more than 8 degrees.
2. In Part 1: If there is a conflict between two possible paths, then the one with lower angle of incidence is given preference.
3. In Part 2: Possible paths of only upto 8 PRCs range are checked. This approximation has been made after observing data from the muon detectors.
4. The CORSIKA simulations were generated for an energy of 20TeV with 1000 showers.
5. In order to concentrate the flux of the muons to one particular module, the position coordinates of each muon were shifted so that they are incident on that module. The shifting is done by generating random numbers for the position coordinates within the range of the module's spatial coordinates.
6. The energy threshold for muons has been set to 1GeV in the CORSIKA simulation, corresponding to the actual energy threshold of the large area muon detectors of GRAPES-3.

6. Functions and their descriptions

The entire program is divided into several functions which individually perform some operations. These funtions and their operations are described below:

1. *main* ( )*:* This function is executed at the starting of the program.
2. *readcoord* ( )*:* Reads and stores the coordinates of each module and their PRCs.
3. *InitCounterHits* ( )*:* Intializes the array CounterHits[][][].
4. *StoreCounter* (int*)*:* Stores an array which is used to plot the actual paths of the muons.
5. *initCounter* (int*)*:* Initializes the array for storing the PRC hits.
6. *angle (*double, double, double*):* Finds the angle of incidence of the muons.
7. *checkCounterHits* (double, double, double, double, double, int): Using the simulation data, it finds out the actual path of the muons and also generates the file which indicates muon detection by PRCs.
8. *Projection* (double, double, double): Finds the projection of the muon on different planes.
9. *Reconstruction* (int, float*, float*): Function used for starting the reconstruction algorithm.
10. *Reconstruct_Part1* (int, float*, float*, int*, int*): Performs reconstruction of muons as mentioned in 'Part 1' of the Algorithm section.
11. *Reconstruct_Part2* (int, float*, float*, int*, int*) : Performs reconstruction of muons as mentioned in 'Part 1' of the Algorithm section.
12. *DrawActualPath* (int*) *:* Plots the actual paths of the incident muons on the module on a canvas.
13. *DrawReconstruction* (int, float, float) : Plots the reconstructed paths of the incident muons on the module on a canvas.

7. System requirements

The simulations required for developing and testing the program were generated on a multi-core processor computer having 48 computing cores supported parallel processing. This system is available at TIFR.

This program has been run and tested on computers with intel i5 processor with a clock speed of 1.5Ghz running Ubuntu OS in a dual boot system with 4GB RAM.
GCC compiler is required.
ROOT should be installed and executable via any directory.
CORSIKA is required for generating simulations.

8. Using the program

The program requires basic knowledge of C++ programming for execution.

Using with simulated data

1. Create a .root file of the simulated data.
2. Open the file *corsikarootreader.cpp* in a text editor.
3. In the function *main*(), change the filename and address of the simulation .root file accordingly.
4. Open terminal and go to the directory where the file *corsikarootreader.cpp* is stored.
5. Compile the program using the *make* command.
6. Run the program using the command *./corsikarootreader*

Using other sources of muon detection data

In order to use any other source,

1. Remove (or comment the parts where simulated data is being used).
2. The array, *CounterHits [<module#>] [<layer#>][<PRC#>]* is used to store the PRC muon detection data.
3. If the value is 0, it indicates that no muon has been detected by the particular PRC.
4. For any other positive value of the variable, it indicates that the particular PRC has detected a muon.
5. Write a function in order to initialize this array with another source of muon detection data.
6. Run the program as mentioned previously.

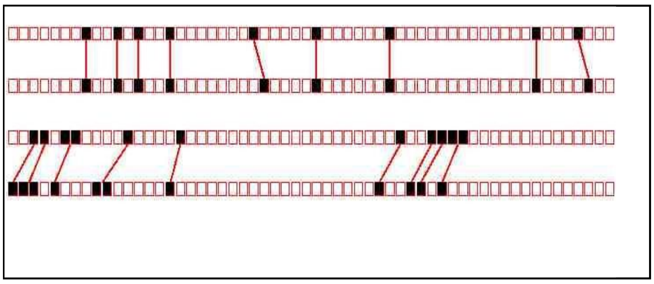
In the output canvas of the program, four separate layers of boxes are drawn. Each box represents a PRC. The boxes which are fully filled with black color represent those PRCs which have detected muon(s) while others have not detected any muon. Since layer 0 and layer 2 lie in the same plane which is orthogonal to the plane of layer 1 and layer 3, the paths will be drawn as projections on these planes.
The first pair of layers from top is the layer 3 and layer 1 while the next pair is of layer 2 and layer 0.

9. Case Study 1

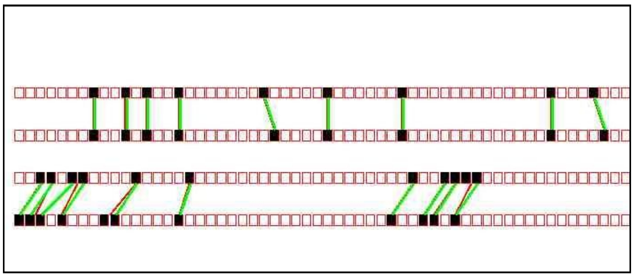
In order to represent the ability and the extent to which the program is able to reconstruct the incident muon paths, an example is demonstrated in the following part of the document.

Source of muon detection data: Simulation file generated from CORSIKA simulation.
Simulation File Title: DAT000020.root
Energy: 20TeV
Number of showers: 1000
Shower number 30:

Actual muon paths (in red) plotted on a canvas:



Total number of actual paths in both sets of layers = 9
Reconstructed muon paths (in green) along with actual paths (in red) plotted on a canvas:

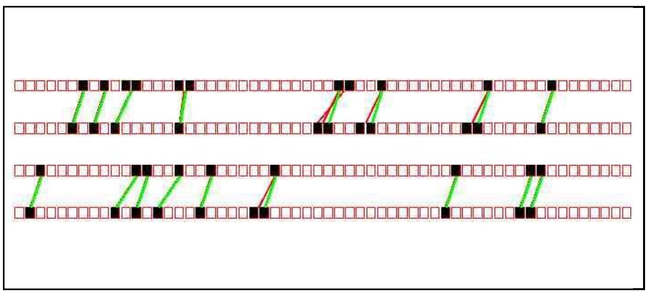


Total number of reconstructed paths in the set of layer 3 and layer 1 = 9
Total number of reconstructed paths in the set of layer 2 and layer 0 = 10
As observed, there is 100% accurate reconstruction for the set of layer 3 and layer 1 while there is a slight error for the set of layer 2 and layer 0.

Reason for the error:
There is an extra reconstructed path generated for the set of layer 2 and layer 0. As observed from the actual path, a muon passes through two counters of layer 2 but only from 1 counter of layer 0. That causes the extra reconstructed path.

10. Case Study 2

Source of muon detection data: Simulation file generated from CORSIKA simulation.
Simulation File Title: DAT000020.root
Energy: 20TeV
Number of showers: 1000
Shower number 69:
Actual muon paths (in red) superimposed with reconstructed muon paths (in green) plotted on a canvas:



Total number of actual paths in both sets of layers = 9
Total number of reconstructed paths in the set of layer 3 and layer 1 = 8
Total number of reconstructed paths in the set of layer 2 and layer 0 = 9

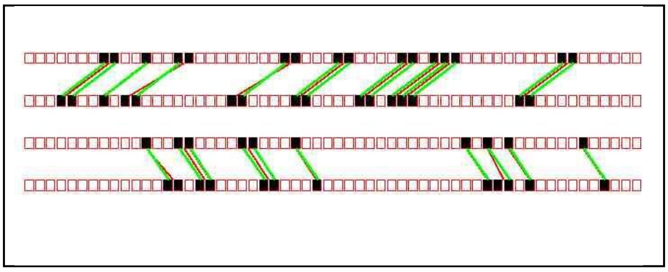
As observed, there is 100% accurate reconstruction for the set of layer 2 and layer 0 while there is a slight error for the set of layer 3 and layer 1.

Reason for the error:
Starting from the left, the first error occurs when two muons pass from two adjacent PRCs of layer 3 and then cross their paths to pass through two adjacent PRCs of layer 1. The algorithm is not able to account for this behavior and has reconstructed only a single path.
Other instances when the reconstructed path (green) does not completely superimpose on the actual path (red) occur due to a single muon passing through two PRCs. This causes a slight deviation of the reconstructed paths from the actual path.

11. Case Study 3

Source of muon detection data: Simulation file generated from CORSIKA simulation.
Simulation File Title: DAT000020.root
Energy: 20TeV
Number of showers: 1000

Shower number 90:
Actual muon paths (in red) superimposed with reconstructed muon paths (in green) plotted on a canvas:



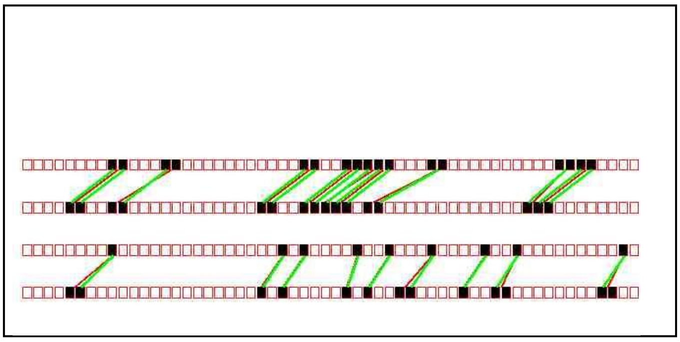
Total number of actual paths in both sets of layers = 9
Total number of reconstructed paths in the set of layer 3 and layer 1 = 14
Total number of reconstructed paths in the set of layer 2 and layer 0 = 10

Reason for error:
As observed, there are several instances when muons pass through two PRCs in both the sets of layers.
Therefore, whenever there is only one actual path, due to multiple PRC hits, two or more paths are reconstructed.
Although the number of reconstructed paths is more than the actual paths, the angle of all the reconstructed paths is same for a particular actual path.

12. Case Study 4

Source of muon detection data: Simulation file generated from CORSIKA simulation.
Simulation File Title: DAT000020.root
Energy: 20TeV
Number of showers: 1000

Shower number 142:
Actual muon paths (in red) superimposed with reconstructed muon paths (in green) plotted on a canvas:

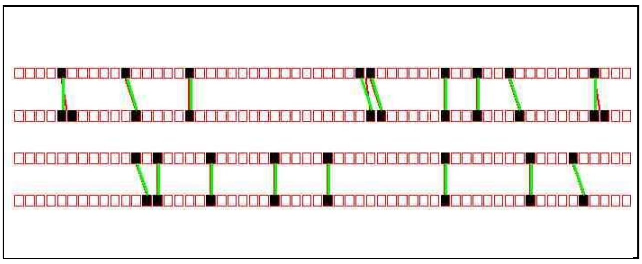


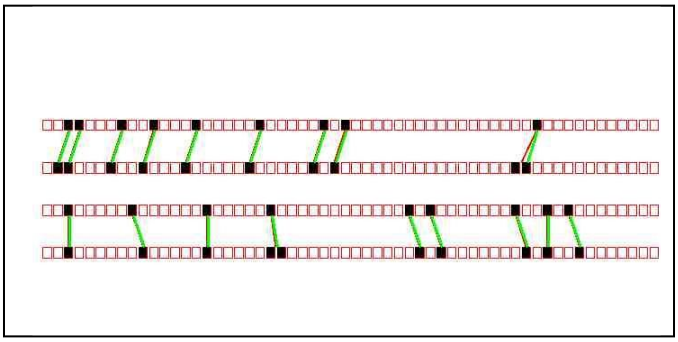
Total number of actual paths in both sets of layers = 9
Total number of reconstructed paths in the set of layer 3 and layer 1 = 9
Total number of reconstructed paths in the set of layer 2 and layer 0 = 8

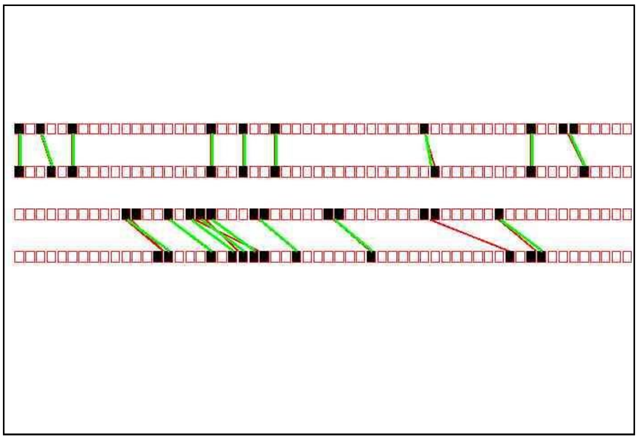
As observed, the reconstruction is 100% accurate for paths between layer 3 and layer 1.

Errors occur in reconstruction between layer 2 and layer 0.
Reason for error:
The error occurs when a single muon passes through two PRCs.
In another instance, when no path is reconstructed for an actual muon path occurs as the angle of incidence is too high and is determined to be improbable by the algorithm.

13. Examples







14. Acknowledgement

The algorithm has been developed with the support of the GRAPES-3 collaboration.