

# Cosmic-ray Monte Carlo simulation using Persistent Object Manager.

Continuation of the POM documentation: [POM Docu](#), [POM Gr Docu](#), and [POM FFT demo](#).

**NOTE:** The package Gr has to be installed and compiled in order for the plots to be visible. If this document shows "alien" objects (grey rectangles with crosses) you need to install the Gr package, and then re-open the document. You can obtain Gr from the same source that provided you with POM.

```
DEFINITION PomCosmicMonteCarlo;
```

```
VAR
```

```
cylHeight      : REAL;      (*scintillator cylinder height*)
cylRadius      : REAL;      (*scintillator cylinder radius*)
doAnalytic     : BOOLEAN;   (*create and show the analytic solution?*)
iterations     : INTEGER;   (*how many cosmic-ray mu-mesons in Monte Carlo run?*)
runs           : INTEGER;   (*how may MC runs? (not very useful; suggest 1)*)
unit           : REAL;      (*unit length to propagate the ray, default 1 mm*)
xyPlot        : BOOLEAN;   (*show the graphical X-Y view of the MC?*)
vertCut       : BOOLEAN;   (*show vertical or horizontal live illustration*)
showRays      : BOOLEAN;   (*show the rays inside the cylinder?*)
```

```
PROCEDURE ClearMain;      (*clear main POM tree; discard whatever data is there*)
PROCEDURE LoadAux;       (*load aux POM tree from disk*)
PROCEDURE Run;           (*run Monte Carlo*)
```

The "show" commands insert the histograms, if there are any currently in memory, into the most recently focused Gr viewer. Any Gr viewer that has been clicked into will be used as the target. The most convenient method is to create a fresh Gr viewer using a menu command, and then click the "show" commands to insert the MC histograms of interest.

```
PROCEDURE ShowPathAnal;   (*show the analytical approximation of the energy deposit*)
PROCEDURE ShowPathMC;    (*show the Monte Carlo histogram of the energy deposit*)
PROCEDURE ShowThetaAnal; (*show the analytical histogram of angular distribution*)
PROCEDURE ShowThetaMC;   (*show the Monte Carlo histogram of angular distribution*)
PROCEDURE UpdateTreeView; (*refresh the display of the Tree View controls*)
```

```
END PomCosmicMonteCarlo.
```

The objective of this software was energy calibration for the experiment performed by Daniel Miner for his Summer 2003 Research Experience for Undergraduates (REU) at the Department of Physics and Astronomy at the University of Rochester. We measured the lifetime of cosmic-ray  $\mu$ -mesons stopped in a 5" high by 6" diameter cylinder made of plastic scintillator, following the method from the book *Experiments in Modern Physics* by Adrian C. Melissinos and Jim Napolitano. In a nutshell,  $\mu$ -mesons are produced in the upper atmosphere by high-energy cosmic rays (mostly protons) that arrive from the outer space, and then shower down to the Earth surface with the intensity of roughly 1 meson per minute per 1 square cm. Most of the  $\mu$ -mesons are very energetic and pass freely through whatever obstacles they encounter (walls, furniture, or human bodies). Fewer than one particle in a thousand happens to be near the end of its range in matter, and it stops in whatever piece of material it encounters. It then roams around, until it spontaneously decays emitting two neutrinos and an electron. One can measure the lifetime of the stopped  $\mu$ -mesons, and possibly their other characteristics such as spin, by observing the decay events in a suitable detector. In our case, we used a large piece of transparent plastic scintillator in which the  $\mu$ -mesons stopped and then decayed. The events of interest

had the following characteristics: a pulse due to the initial  $\mu$ -meson impact triggered the electronic readout. Another pulse due to the decay was observed shortly thereafter. The waveforms containing two pulses in short succession were therefore recorded and stored for offline analysis. Of particular interest to BlackBox user is the fact that both the data acquisition and subsequent analysis were performed with BlackBox software, using Gr for data display and POM to manage the data.

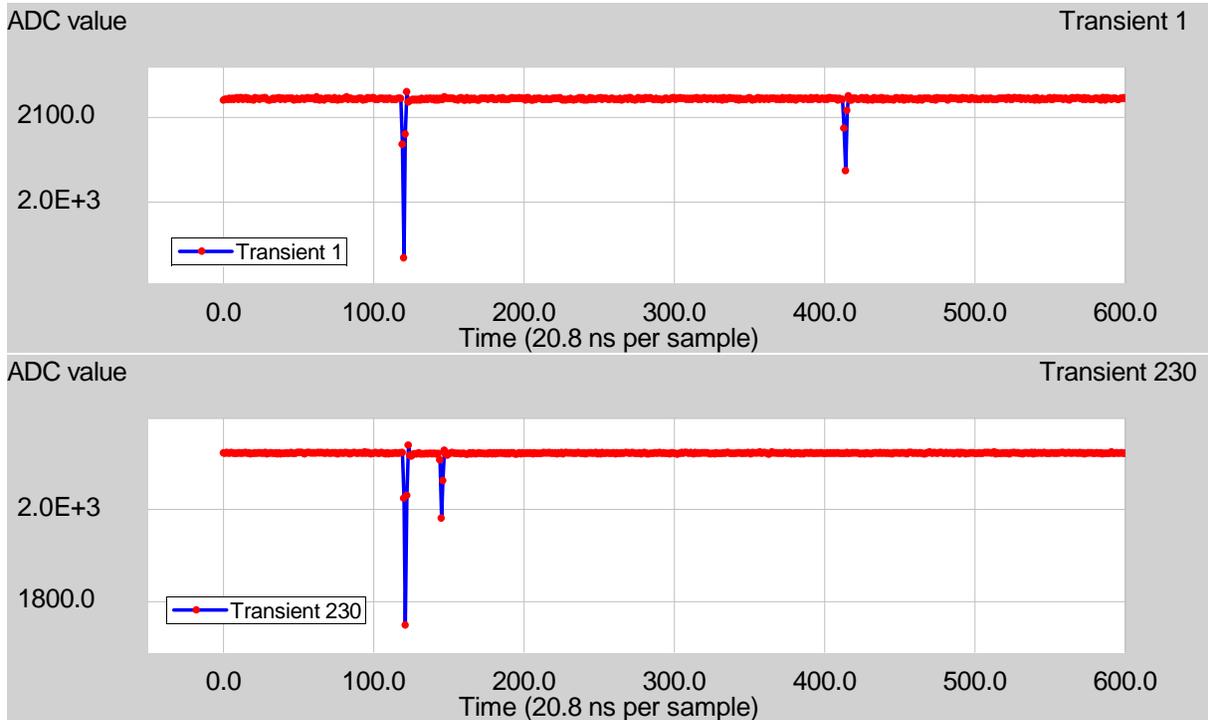


Figure 1. Examples of two waveforms show the first pulse due to a  $\mu$ -meson impact and second pulse due to its decay within the volume of a 5"x6" BC-400 plastic scintillator. Red dots are ADC samples, the blue line is to guide the eye.

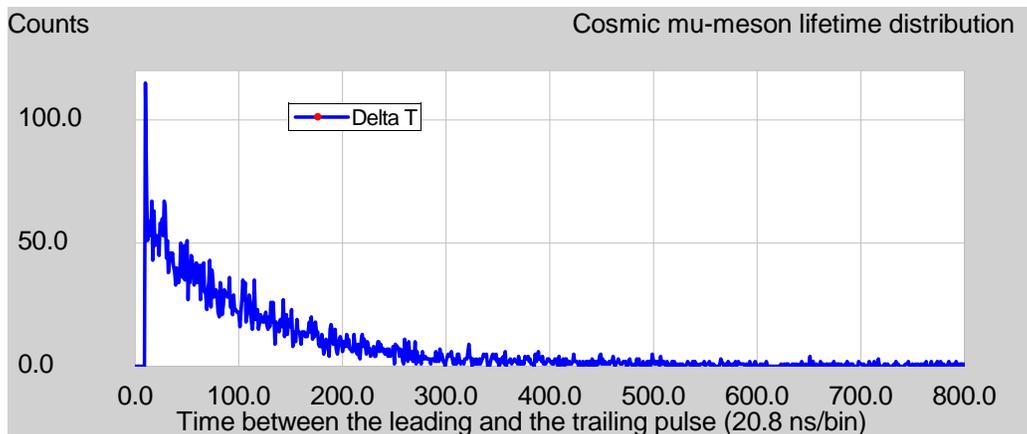


Figure 2. An exponential interval distribution between the 1st and 2nd pulses in Fig. 1 is caused by the decay of stopped  $\mu$ -mesons. The peak near channel 0 is due to pulses that are close together and partly overlap.

Concerning the experimental details, we purchased the scintillator type BC-400 from [www.oetech.com](http://www.oetech.com) in New Mexico. We used optical grease to couple the scintillator to a Hamamatsu phototube type R1847-13, which we then polarized with -1000 Volts. The voltage impulses were delivered to and digitized by a

waveform digitizer type DDC-1 that was designed and built by W.S a year before. The unit operated with 12-bit resolution and 48 MHz sampling frequency, what defined the time unit in this experiment ( $1/48 \text{ MHz} = 20.8 \text{ ns}$ ). The embedded software and firmware for the DDC-1 unit was developed the previous year by W.S and another student (Saba Zuberi) for her Senior Thesis. BlackBox was used for data acquisition and analysis. Both the Saba's thesis and the detailed Dan's writeup are available on request from Wojtek.

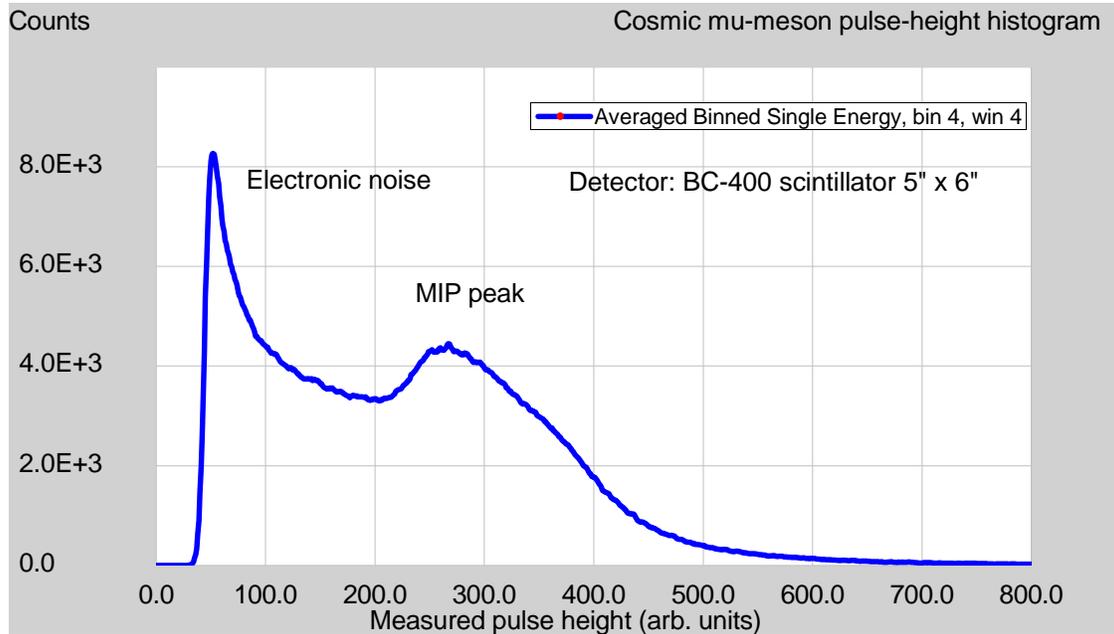


Figure 3. Measured pulse-height distribution of pulses measured with a 5"x6" BC-400 plastic scintillator coupled to a phototube. The cosmic-ray  $\mu$ -mesons caused a "minimum-ionizing" peak at around the channel number 270. The sharp peak in channel 50 is due to the measurement threshold. Pulses below the threshold were cut by the DDC-1.

The energy histograms of both the leading and trailing pulses were generated offline (not shown in this writeup). The question then arose, what was the energy calibration in terms of absolute units, namely mega-electron-volts (MeV)? Fortunately, the experiment was self-calibrating because the energy loss of high-energy  $\mu$ -mesons (the ones that were *not* stopped in the scintillator) caused a pronounced "minimum-ionizing particle" (MIP) peak in the respective histogram that we measured online. The histogram is shown in Figure 3, and the MIP peak is clearly visible. Besides the MIP peak there are also other features, such as the low-energy peak due to electronic noise, and the valley between the two peaks. We decided to calculate the energy distribution, and in particular the energy of the MIP peak, for our particular detector geometry, namely a 5" by 6" plastic cylinder oriented vertically. (A professional high-energy physicist would use the simulation code GEANT available from CERN, but we wanted to understand what we were doing, hence we wanted to develop the simulation from scratch.)

The Monte Carlo algorithm. The algorithm works as follows. Imagine a hollow sphere encompassing the scintillator cylinder in the middle. Every point on the sphere is equally probable to see a  $\mu$ -meson passing through. (This particular assumption will be discussed later, because it may lead to subtle errors.) We only need to consider the upper hemisphere, because the  $\mu$ -mesons are all going down. We therefore pick up any point on the upper hemisphere, with equal probability, and begin tracing a  $\mu$ -meson going down from that location. The ray is traced until it leaves the sphere. (Some rays are pointing away from the sphere, and we discard them right away.) Inside the sphere, if the ray enters the cylinder, we begin accumulating its "path length" until it leaves the cylinder. The "path length" for each individual ray is (by definition) proportional to the energy deposited in the cylinder, which is our desired observable. We accumulate the "path length" values in a histogram.

There are a couple of Jacobians to be considered. The ray tracing is performed in Cartesian coordinates. Because of the symmetry of the problem the rays are initially chosen in spherical coordinates. The empirical angular distribution of incoming mesons is proportional to  $\cos^2(\theta)$ , where  $\theta = 0$  corresponds to the zenith. The formula in polar coordinates gets an additional Jacobian factor  $\sin(\theta)$ . The probability density to draw the ray direction from is therefore  $\sin(\theta)*\cos^2(\theta)$ . This is used both in Monte Carlo and in the analytic section of the program. In the latter, when we want to compare the results with an analytic formula, the analytic transformation between  $\theta$  and the path length has a Jacobian of its own. Please see the comments in the code concerning the latter.

There is an omission in the algorithm (discovered on Jan/19/05). In case the ray points outside the sphere from its starting point, the current version ends tracing this particular ray. However, in physical reality such a ray must have traveled across the interior of the sphere (the  $\mu$ -meson was not created in its seed point on the sphere), so we should trace such a ray backwards towards the zenith rather than down. So, the correct algorithm should be:

- get the seed point on the sphere;
- if the ray enters the sphere, trace it down;
- if the ray leaves the sphere, trace it up.

It is a small correction to the algorithm that is only important near the equator of the test sphere (where it gets heavily suppressed by the  $\cos*\cos$  factor). For the principal correctness it should be done.

A possible sticky point that I am a bit worried about, is choosing the "entry point" on the sphere with equal probability. This is justifiable on physics grounds, because every point in space is as good as any other from the point of view of the  $\mu$ -meson flux coming from the upper atmosphere. However, if we think of a thin shell rather than of an infinitely thin sphere, there might be an additional weighting function because the walls of the shell are tilted near the equator, so there is more volume there. Thinking of an infinitely thin shell I decided this extra volume is unwarranted, and I did not consider the extra weighting factor. In a more formal language, there may be an additional Jacobian sitting there that I have erroneously forgotten. If someone wants to comment then please send me an e-mail.

The assumptions of the simulations are as follows:

1. The  $\mu$ -mesons arrive from zenith with  $\cos^2(\theta)$  distribution, where  $\theta=0$  points directly up. This angular

distribution is known experimentally [*Particle Data Book*, Particle Data Group, Berkeley, 2000].

2. Except for those that stop and decay (a very small fraction), the  $\mu$ -mesons lose constant energy per unit path in the plastic. We can approximate the energy loss in Figure 3 with a constant\*path length in the plastic, where the constant value is 2.3 MeV/cm [*Particle Detectors*, Claus Grupen, Press Syndicate of the University of Cambridge, New York, 1996].
3. The energy smearing in the detector is not accounted for. The smearing comes from two physics effects:
  - the energy fluctuations due to the statistical nature of the energy loss, and
  - the imperfect collection of light by the phototube.

It is not realistic to expect that the energy resolution of our detector is infinitely good, as it is assumed in this simulation. Plastic scintillators are known to have rather broad energy resolution due to the smearing mentioned above. A realistic simulation would smear the simulation with a Gaussian function of some reasonable width (20% is not unreasonable). Lacking any data on the energy resolution of our detector we have not done this, however. We rather believe that the non-smearred peak location can be compared with the smearred peak seen in the data (i.e., smearing would preserve the mean value of the MIP peak).

A ray-tracing Monte Carlo simulation of the path length distribution through the cylinder, scaled by an approximate MIP energy loss in the scintillator plastic, is compared to the pulse-height spectrum of the single pulses, as non-stopped muons can be approximated as MIP's. Admittedly, the algorithm derivation was quite prone to errors because a few Jacobians had to be factored into the calculation: the Jacobian of spherical coordinates, as well as a separate Jacobian transforming the theta distribution into the path-length distribution. We argued with Dan for quite a while, and at the end we did not quite agree on all the sine and cosine factors. (This is reflected in the opening comment.) I hope the version I put on the web is mathematically correct, but I will not swear by it one hundred percent.

There are two Monte Carlo distributions and two analytical distributions.

1. The path-length distribution, proportional to energy loss. To be compared with Figure 3.
2. The theta distribution that could be compared with directional measurements, if we had a direction-sensitive detector.

The analytical distribution #1 (path length) does not take into account the sides of the cylinder. It can only account for the energy peak that would be observed with a very wide, flat disk where the side walls would be negligible. The comparison between the analytical and the Monte Carlo distributions can be done by running the MC for a very flat disk (width:height ratio of 10:1 or more). Keep in mind that both the analytical and MC distributions may have the same Jacobian problem!

## How to run the simulation:

Execute the following commanders, or use menu items to open the Cosmic Monte Carlo program.

```
! "StdCmds.OpenAuxDialog('Pom/Rsrc/CosmicMCPanel', 'Cosmic Monte Carlo Simulation')
```

It is not a bad idea to clear the main POM tree of old results prior to running the simulation. Check the xyPlot

check box and you will see a live display. Run with as few as 100 rays to understand the geometry. Run with as many as 100,000 rays to understand the results. Always run a single run (runs = 1) to avoid too many histograms. The option of multiple runs is there only to show the programming possibilities. After you have performed a run, execute the following commander and examine the histos. You can also open the result panel by pressing a button labeled "Show results", located in the MC panel.

```
! "StdCmds.OpenAuxDialog('Pom/Rsrc/POMPanel', 'Cosmic MC Simulation Results')"
```

### Example of Monte Carlo results:

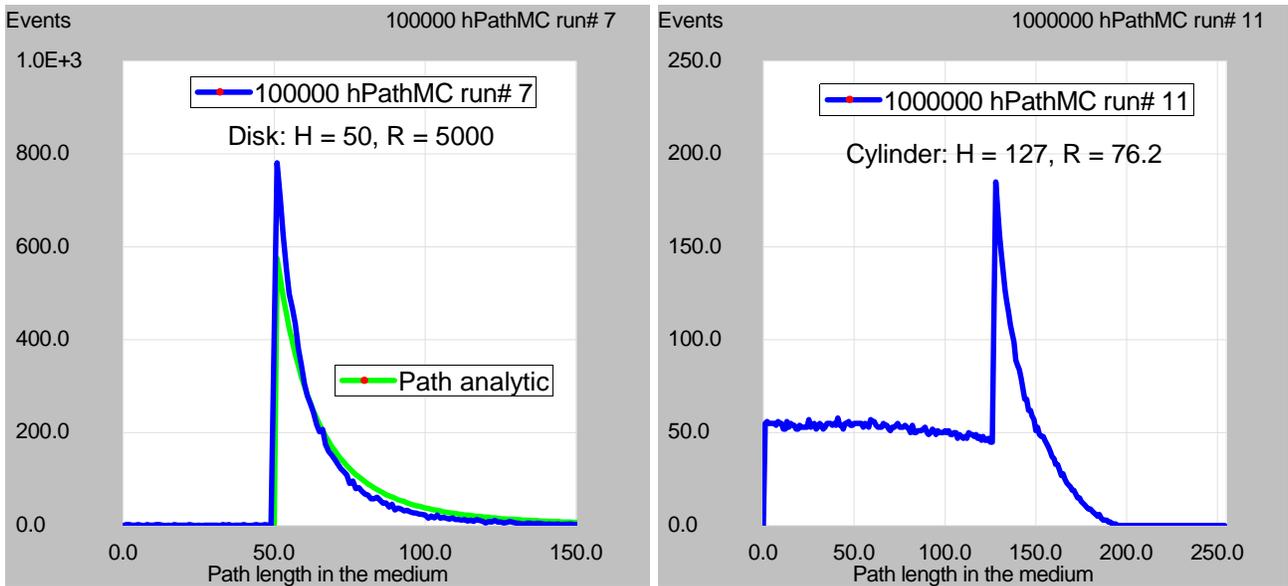


Figure 4. Left panel: simulated path-length distributions for very flat disks show a reasonable agreement between the analytical and MC distributions. Right panel: simulation of the actual experimental geometry shows the peak due to crossing the center of the cylinder, and a flat distribution due to intersecting the side walls.

### Explanation of variables:

The global variables have been explained at the beginning, not to be repeated.

### Explanation of procedures:

```
PROCEDURE ClearMain;          (*clear main POM tree; discard whatever data is there*)
PROCEDURE LoadAux;           (*load aux POM tree from disk*)
PROCEDURE Run;               (*run Monte Carlo*)
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The "show" commands insert the histograms, if there are any currently in memory, into the most recently focused Gr viewer. Any Gr viewer that has been clicked into will be used as the target. The most convenient method is to create a fresh empty Gr viewer using a menu command, and then click the "show" commands to insert the MC histograms of interest.

PROCEDURE ShowPathAnal; (\*show the analytical approximation of the energy deposit\*)  
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PROCEDURE ShowThetaAnal; (\*show the analytical histogram of angular distribution\*)  
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PROCEDURE UpdateTreeView; (\*refresh the display of the Tree View controls\*)

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