The Monte Carlo Method: Versatility Unbounded In A Dynamic Computing World
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GEOMETRY EQUIVALENCE METHOD IN MONTE CARLO SIMULATION FOR AERIAL RADIATION SURVEY

ZHU Jin Hui, ZHAO Jun, HUANG Liu Xing, NIU Sheng Li and PENG Yu
Northwest Institute of Nuclear Technology
P. O. Box 69-12, Xi'an, 710024, China
zhujinhui@tsinghua.org.cn

ABSTRACT

A kind of geometry equivalence method to solve low-probability problem in Monte Carlo particle transport simulation is presented in the paper. For large-source-and-small-detector cases, such as in situ gamma ray spectrometer, the detecting probability in analog Monte Carlo simulation is too low to get results. When the main medium in large geometry is homogeneous in two-dimension, as for in situ spectrometer, the method is fit to change the simulation as small-source-and-large-detector. So it can raise the detecting probability extremely and make it easy to simulate in situ spectrometer.

In the paper, the Geometry Equivalence Monte Carlo Method are introduced, including theoretic analysis, verification and comparison with analog simulation. All the results show that the method worked efficiently.

Key Words: Monte Carlo Simulation, Low-probability problem, Geometry Equivalence Method, spectrometer

1 INTRODUCTION

The Monte Carlo Simulation of the large-source-and-small-detector cases, such as in-situ measurement of environmental radiation, are typical low-probability problems, which are solved usually by the adjoint Monte Carlo technique and the point probability method. The adjoint Monte Carlo technique, which is difficult to be programmed, simulates an inverse process of a real physical process. The point probability method, which estimates the point flux, neither simulates a particle traveling to a point detector, nor calculates the response of a detector. It is far form the needs for solving a real problem.

In the in-situ measurement of environmental radiation case, the ground and the air are infinite and homogeneous horizontally. According to the characteristic of the problem, a geometry equivalence method—the particle is emitted from a small source and received by a large detector—is used. The method, which is an inverse of the geometry instead of the physical process, is different from the adjoint Monte Carlo technique.

2 THEORETICAL ANALYSIS

Assuming the probability of finding a recorded particle, which is resulted form a particle emitted form point $\vec{r}_0(x_0, y_0, z_0)$, in dV at point $\vec{r}_1(x_1, y_1, z_1)$ with a scope of energy within $E \sim E + dE$ and direction within $d\vec{\Omega}$ is dn. The transition function is defined as follows:

$$T(\vec{r}_0 \to \vec{r}_1) = \frac{\mathrm{d}n}{\mathrm{d}V\mathrm{d}E\mathrm{d}\vec{\Omega}} \quad \textbf{(1)}$$

Transition function $T(\vec{r}_0 \to \vec{r}_1)$, describing the contribution of $\vec{r}_0(x_0, y_0, z_0)$ traveling to $\vec{r}_1(x_1, y_1, z_1)$, is related to the energy, the direction of the emitted particle, the medium and the type of recorded particle. As to the ground and the air, their parameters have spatial invariability horizontally, thus to the transition function $T(\vec{r}_0 \to \vec{r}_1)$ as shown in figure 1.

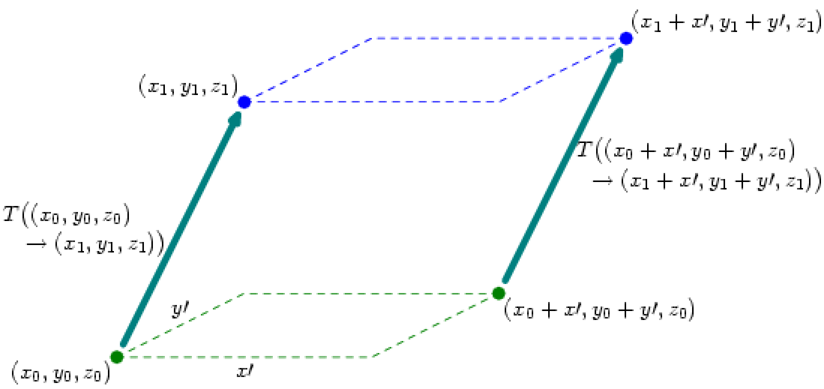

Figure 1. The space-invariability of transition function

$$T((x_0, y_0, z_0) \to (x_1, y_1, z_1)) = T((x_0 + x', y_0 + y', z_0) \to (x_1 + x', y_1 + y', z_1)) \quad \textbf{(2)}$$

Located the detector at point $(0,0,z_1)$; after the substitution $x' = -x_0, y' = -y_0$ was made, equation (2) takes the form

$$T((x_0, y_0, z_0) \to (0,0,z_1)) = T((0,0,z_0) \to (-x_0, -y_0, z_1)) \quad \textbf{(3)}$$

The expression (3) shows that the properties of the particles6 through the detector $(0,0,z_1)$ resulted from the point-source (x_0, y_0, z_0) are equal to that through $(-x_0, -y_0, z_1)$ resulted from the point-source $(0,0,z_0)$.

The number of recorded particles through dV at the point $\vec{r}_1(x_1, y_1, z_1)$ with a scope of energy within $E \sim E + dE$ and direction within $d\Omega$ resulted from the infinite body source is

$$\mathrm{d}N = \mathrm{d}V\mathrm{d}E\mathrm{d}\vec{\Omega}\int_{\infty} \rho_s(x_0, y_0, z_0) T((x_0, y_0, z_0) \to (0,0,z_1))\mathrm{d}x_0\mathrm{d}y_0\mathrm{d}z_0 \quad \textbf{(4)}$$

Where $\rho_s(x_0, y_0, z_0)$ is radiation density, describing the number of source particle emitted form tiny volume $\mathrm{d}x_0\mathrm{d}y_0\mathrm{d}z_0$ in the (x_0, y_0, z_0). From (3) and (4), we will get

$$\mathrm{d}N = \mathrm{d}V\mathrm{d}E\mathrm{d}\vec{\Omega}\int_\infty \rho_s(x_0, y_0, z_0)T((0,0,z_0) \to (-x_0, -y_0, z_1))\mathrm{d}x_0\mathrm{d}y_0\mathrm{d}z_0 \quad \textbf{(5)}$$

Thus, the body source to point detector case is converted to the line source to the surface detector case. The conversion occurs only horizontally Because of the vertical independency. The essence of this conversion is changing surface-to-point to point-to-surface, and we name it geometry equivalence method.

It is noticed that the change of the unit of the physical quantity while conversing. Before converted, body source is measured in body density and the detector is a point; after converted, line source is measured in line density and the detector is a surface. According to the theoretical analysis above, it occurs in the process of integral to x_0, y_0 and z_0.

If the body source radiates various particles with different energy and in different directions, the method also satisfied to the case by integrating or summing of transition function to the energy of the source particle, emitted direction and the type of the source particle.

No statistical knowledge and Monte Carlo Method be used in the theory analysis above, so that the formula (5) is fit for the Monte Carlo simulation and no error be introduced.

3 IMPLEMENTATION IN CODE SYSTEM

Originating from formula (1), a large number of source particles are emitted from the point $\vec{r}_0$ will result few records at point $\vec{r}_1$ because that it is a low-probability event, when conducting MC simulation directly even more worse from formula (4). From formula (5) however, the source particles are sampled in a line and recorded in a plane at the height of z_1. The probability is much more larger. Theoretically, if it is an infinite body source, the sample efficiency will increase by infinite times. Thus, the geometry equivalence method can raise the sample efficiency extremely.

In order to apply the geometry equivalence method to the Monte Carlo simulation of the coupled transport of electrons and photons, the general-purpose program package EGS4 is used and the version here is EGSnrc. EGS is an open program package. Its main program, record-output program and the geometry program are edited by users who can control the flow of the program. EGS is fit for any technique.

The sample and record process of an ideal instance is described as follows: the radiation source is infinite slab with a thickness of d, homogeneous radiation density ρ_s, and some kinks of distributions of the energy and the direction. The differential current (the number of γ photon in unit area) of γ photon through the horizontal plane including the point $(0,0,z_1)$ is recorded.

The initial position $(0,0,z_0)$ of the γ photon is defined by sampling z_0 in the line with a length of d; the initial energy and the direction are sampled according to their distributions respectively. In an EGS run, all γ photon though the plane $z = z_1$ is recorded. If the number of the initial γ photons is N, with n recorded, then the differential current is $d\rho_s\, n/N$.

4 VALIDATION OF THE METHOD

To verify the feasibility of the method, a comparison has been carried out between the geometry equivalence method and the analogue simulation to the same problem. A real infinite body source can't be sampled directly, so a body source with a diameter of 200m and a thickness of 5cm is used. An isotropic γ radiation source with the energy of 2.62MeV is distributed in the body source homogeneously. In the analogue simulation, the horizontal record plane, which is 1m above the earth and 8m in diameter, is much smaller than the source . In the geometry equivalence method case as shown in figure 2, the current of a point in air is recorded.

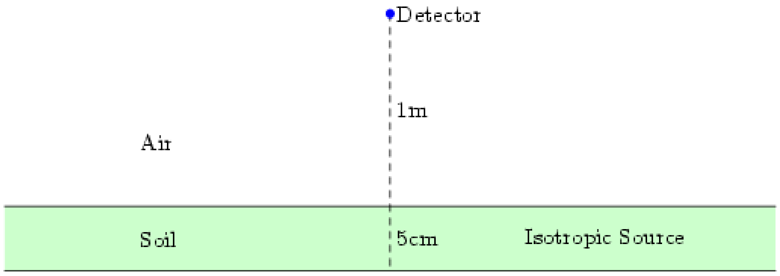

Figure 2. The geometry of the example

The geometry equivalence method is applied to solve the problem by using EGSnrc and the analog simulation is applied by using a general Monte Carlo N-particle transport code—MCNP. The energy spectrums at the plane with a height of 1m, which are shown in figure 3, are recorded by two methods respectively. From the date of the figure, it is known that the two spectrums are very close. The feasibility of the geometry equivalence method is verified.

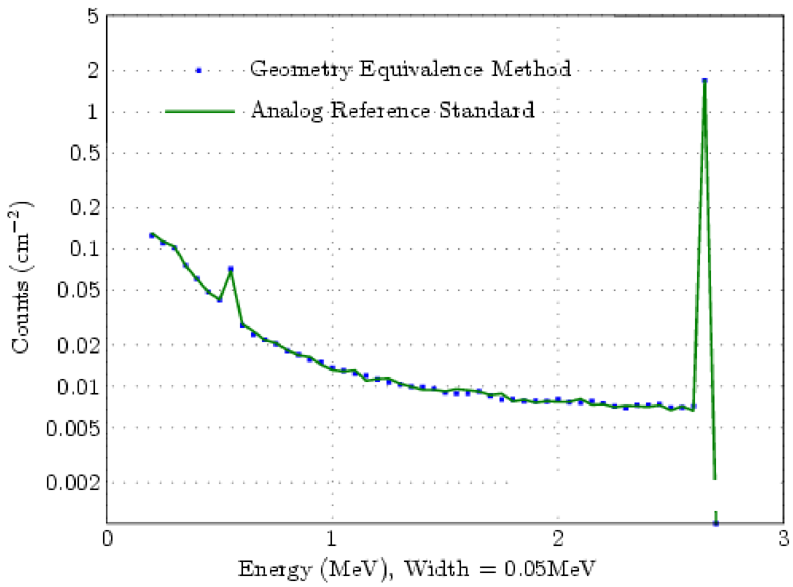

Figure 3. The energy spectrums of two methods

There are 10^6 source particles which are simulated in the geometry equivalence method and the number is 2×10^8 in the analogue simulation. The statistical error of the geometry equivalence method is about a half of the analogue simulation. It can be estimated that the sample efficiency is raised of the order of 800 times. In above analogue simulation a detector plane with a diameter of 8m is used as “small detector plane”. The statistical error would increase and the analogue simulation wouldn’t be fit for this situation if a smaller plane were used.

The premise of using the geometry equivalence method is that the medium is a spatial invariant in horizontal direction. Because the detector isn’t homogeneous horizontally, a geometrical module of transmission in detector is need inserted if the process of particle transmission in detector need simulated. The geometry equivalence is finished when the particles enter the plane in which the detector situated, and then the particle is simulated by analogue simulation.

5 SUMMARY

A geometry equivalence Monte Carlo simulation method is introduced above and it is validated by a simple instance. Contrast with analogue Monte Carlo simulation, the geometry equivalence can raise the sample efficiency extremely of the problem that its geometry is homogenous horizontally.

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