The Monte Carlo Method: Versatility Unbounded In A Dynamic Computing World
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MONTE CARLO SIMULATION FOR AIRBORNE GAMMA RAY SPECTROMETRY

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ABSTRACT

The aerial measuring terrestrial gamma radiation from airborne platforms is a useful method for characterizing the radiation levels over large areas. Because of the advantage of Monte Carlo method, it is very suitable for simulation of gamma ray transport and interaction with media (soil, air, aircraft and detector), which offer alternative means of estimating detector response and calibration factors for airborne gamma ray spectrometry system. In this paper, the geometry equivalence method Monte Carlo method and simulation code for airborne gamma ray spectrometry are presented and validated, which overcome the difficulty of poor statistics of modeling the large-area-source and point-detector problem. It has been applied to investigate practical airborne gamma ray spectrometry system. The airborne spectrum of gamma ray from ground source and radioactive pads sources were simulated. The response of detector was calculated. The simulated results are accord with that of experiments. The simulated results are combined with experimental data to determine calibration factors of airborne gamma ray spectrometry system and quantitatively analyze aerial measuring data.

Key Words: Monte Carlo Simulation, Airborne Gamma Ray Spectrometry, Detector, Response, Calibration factor,

1 INTRODUCTION

Gamma rays are the most penetrating radiation from natural and man-made sources, and gamma ray spectrometry is a powerful tool for the monitoring and assessment of the radiation environment. Measuring terrestrial gamma radiation from airborne platforms (aerial radiation surveying) is a useful method for characterizing the radiation levels over large areas. Aerial radiation survey methodology has been developed over several decades. However, gamma-ray image quality has often been poor and skilled interpreters scarce. Recent developments in multichannel processing techniques and the use of modern computer data processing has enabled the introduction of new interpretation methods and the achievement of greater reliability in solving geological and environmental problems.

Airborne gamma ray spectrometry as a remote sensing technology (IAEA, 1991 and IAEA, 2 003) is being widely used to map the spatial distribution and concentration of gamma-emitting radionuclides in the near surface, combined with soil sampling and laboratory analyses. The information gathered by airborne gamma ray spectrometry can show the abnormal radiation level of certain area and direct the ground teams effectively and allow the deployment of counter measures where they are most needed.

Because of the advantage of Monte Carlo method, it is very suitable for simulation of gamma ray transport and interaction with media (soil, air, aircraft and detector), which can be use to establish calibration factors combined with experimental data and help make quantify aerial measuring results.

In the following sections, the airborne gamma ray spectrometry system is briefly described first. Second, the Monte Carlo method and simulation code for airborne gamma ray spectrometry are described with analogue simulation based on EGS code system (W.R. Nelson, 1985) for near-source-detector geometries and the geometry equivalence method for extended, far-source-detector geometries relevant to airborne measuring. And then the Monte Carlo method is applied in modeling of practical airborne gamma ray spectrometry system, including simulation of airborne spectrum of gamma ray from ground source and radioactive pads sources. The response of detector is calculated. The simulated results are combined with that of experiments to determine calibration factors of airborne gamma ray spectrometry system and quantitatively analyze aerial measuring data.

2 PHYSICAL MODEL OF AIRBORNE GAMMA RAY SPECTROMETRY

Gamma rays are the most penetrating radiation from natural and manmade sources. Individual radionuclides emit gamma rays of specific energies that are characteristic for an element and isotope. The schematic diagram of airborne gamma ray spectrometry system is shown in figure 1. Spectrometers are mounted in aircraft. The gamma radiation emitted from isotopes in near surface is attenuated in the source region and materials between the source and the detector, and then enters the detector. Measured spectra, from which the source term can be obtained, are comprehensive results of many complicated factors, include the concentration and geometry of the source, the detector response, the source-detector geometry, the height of the detector above the ground, the thickness of any non-radioactive overburden, the response function of the detector, and the other environmental effects such as soil moisture etc.

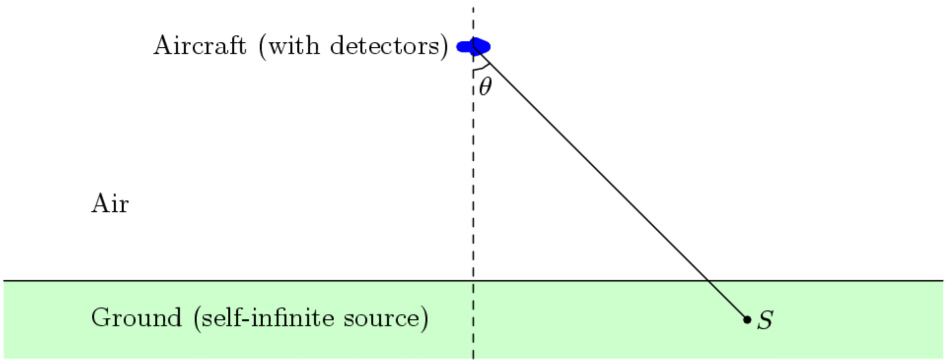

Figure 1. The schematic diagram of airborne gamma ray spectrometry system.

2.1 The sources of gamma radiation

Uranium, thorium and potassium are the only naturally radioisotopes with gamma ray emissions of sufficient energy and intensity to be measurable at the airborne surveying altitude. Uranium, thorium and potassium equilibrium decay series each have characteristic line spectra. These are theoretical abstractions that represent the energy distribution of emitted photons at the source. Each line spectrum shows the energy and relative intensity of gamma ray emissions in the decay series.

The artificial radio-isotopes created during nuclear weapon explosion or in reactors for scientific research and industrial uses. For example, ^{137}Cs, with a single photopeak at 0.662 MeV and has a half-life of about 30 years, is the main gamma-emitting fall-out product from nuclear explosions and accidents.

Radiation not originating from the earth's surface is usually regarded as "background". There are three main sources of background radiation: atmospheric radon, cosmic background, and instrument background.

2.2 Source-detector geometry

Source thickness has a significant effect on the shape of observed spectra. With increasing source thickness there is build-up of the Compton continuum due to scattering in the sources. The photopeaks are thus reduced relative to the Compton background. Since low-energy photons are more easily attenuated than high-energy photons, this effect is more pronounced at lower energies.

The emitted gamma radiation is attenuated in the source and by material between the source and the detector. The shape of the observed spectrum depends on the amount of attenuating mate rial between the source and the detector. With increasing attenuation, the photopeaks are reduced relative to the energy continuum. Measured spectra are thus functions of the concentration and g eometry of the source, the height of the detector above the ground, the thickness of any non-radio active overburden, and the response function of the detector. Typical examples of airborne K, U, and Th spectra (IAEA, 2003) recorded by Thallium-doped sodium-iodide scintillation crystals d etector on the ground using specially constructed radioactive sources is shown in Figure 2. For c alibration, wood was used to shield the detectors from the sources, thus simulating the attenuatio n of the gamma rays by air.

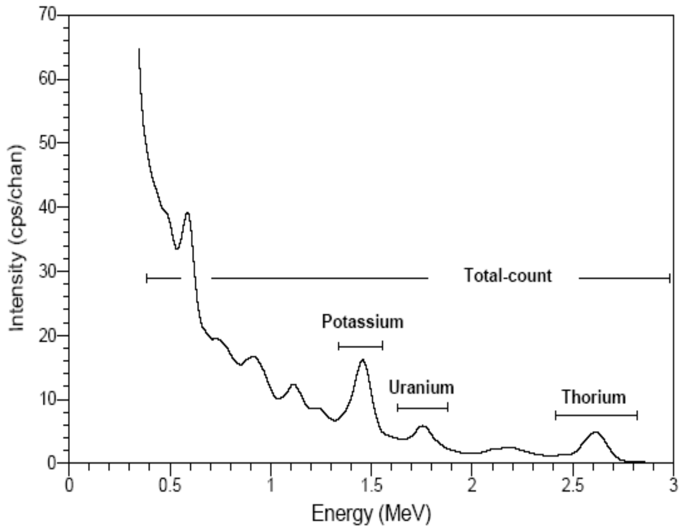

Figure 2. Typical airborne gamma ray spectrum showing the positions of the conventional energy windows.

2.3 Instrumentation and detector response

The used instrumentation is MCA-2 airborne spectrometry system comprise detectors. Each detector package consists of 14 4inch×4inch×16inch NaI crystals and 3.5 inch photomultipliers. Spectrometers record 256 contiguous channels of data, each with 0.012MeV energy width. The energy width of the spectral windows is given as table I.

Table I. The spectral windows of MCA-2

windows	Energy width (MeV)
Total windows	0.408－2.808
Cs windows	0.624－0.708
K windows	1.368－1.572
U windows	1.656－1.860
Th windows	2.412－2.808
Cosmic windows	>2.808

When a gamma ray enters the crystal and strikes an electron, the electron gains energy which is then emitted as a tiny flash of light when the electron returns to its original energy state. The number of flashes is proportional to the gamma ray energy, so that the total light intensity is a measure of the energy of the incoming gamma ray. An array of photomultiplier tubes converts the light into an electrical signal. The spectrometers measure only the gamma radiation which falls within spectral windows of fixed energy width.

The main aspects of the detector response are detector efficiency, directional sensitivity, energy resolution and dead time. Detector efficiency relates to how well the detector absorbs gamma rays. The detector energy resolution is a measure of a detector’s ability to distinguish between two gamma rays of only slightly differing energy. Dead time refers to the finite time required for the spectrometer to process individual photons. Spectrum photopeaks have Gaussian shapes. This is mainly due to the limited energy resolution of NaI detectors.

2.4 Calibration of airborne spectrometry

As recommended by International Atomic Energy Agency (1991), 256 channel spectra are collected and reduced to four standard energy windows. The main corrections that must be applied to airborne gamma ray data are background correction, stripping correction, height correction, and sensitivity correction (reduction to elemental concentrations).

There are four main procedures for acquiring calibration data: high altitude background calibration flights, ground calibrations over radioactive sources to determine stripping ratios, calibration flights over a calibration range to determine height attenuation coefficients and sensitivity coefficients, and flights to measure the radon spectrum.

3 MONTE CARLO SIMULATIONS

Gamma rays interact with atoms of matter by three principal processes (ICRU, 1994):the photoelectric effect, Compton scattering and pair production. The photoelectric effect is the predominant absorption process at low energies, and results in all the energy of a gamma quantum being absorbed in a collision with an electron of an atom. Compton scattering predominates at moderate energies and corresponds to a collision of an incident photon with an electron. The incident photon loses part of its energy to the electron and is “scattered” at an angle to its original direction. Pair production occurs at energies greater than 1.02 MeV. It is the process whereby an incident photon is completely absorbed and results in the creation of an electron-positron pair in the electrostatic field of a nucleus. For gamma rays energies of most practical interest in airborne measuring, Compton scattering is the dominant interaction process. This scattering occurs in the rock/soil near surface, in the column of air between source and detector, in material of aircraft, and in detector itself. A comprehensive solution of the full gamma ray transport problem is complicated, which will be determined by a combination of Monte Carlo simulations and experiments.

In this paper, the Monte Carlo simulations are based on unix version of EGS code system. The EGS computer code system is a general purpose package for the Monte Carlo simulation of the coupled transport of electrons and photons. It is applied directly for near-source-detector geometries. However, as for case of aerial measuring with infinite ground source and detector at altitude, analogue Monte Carlo simulation became too slow to be of practical usage because of the decrease in successful event histories that may cause an increasingly computer time and poor statistical precision. A number of methods such as rejection techniques, systematic sampling, statistical estimation, survival probabilities and weighting schemes can improve the efficiency of detect counting rate. But it cannot trace the gamma ray that enter detector, simulate the energy deposition in crystal and response of detector. To meet this problem, a geometrical equivalent method (J. ZHAO, et al., 2005)is introduced and has been implemented in EGS code system. The schematic diagram of the flowchart of geometrical equivalent Monte Carlo simulation is shown in Figure 3. It is validated with a benchmark model that can be calculated by analogue Monte Carlo method (J.H. ZHu, et al., 2004).

4 RESULTS AND ANALYSIS

4.1 The spectrum of gamma ray from ground source

Consider an isotropic, homogeneous, infinite ground source (1 meter thickness) with natural radioactive isotopes (U, Th, and K, with 1 Bq/cm3 activity) and Cs. The energy spectrum of natural source is taken from IAEA, 1989. The attenuation and transport of gamma ray in soil and air was modeled. The spectrum of gamma ray at altitude 1 meter and 100meter are obtained. The comparison of current rates of direct gamma at 1m and 100m of 4 single energy sources are given in Table II. It shows the attenuation of gamma rays in air of 100 meters height. The comparison of current rates spectrum of 2.615Mev source at 1m and 100m altitude are shown in Figure 4. The comparison of angle spectrum of energy flux rates of 2.615Mev source at 1m and 100m altitude are given in Figure 5.It shows the scattering of gamma rays in air of 100 meters height.

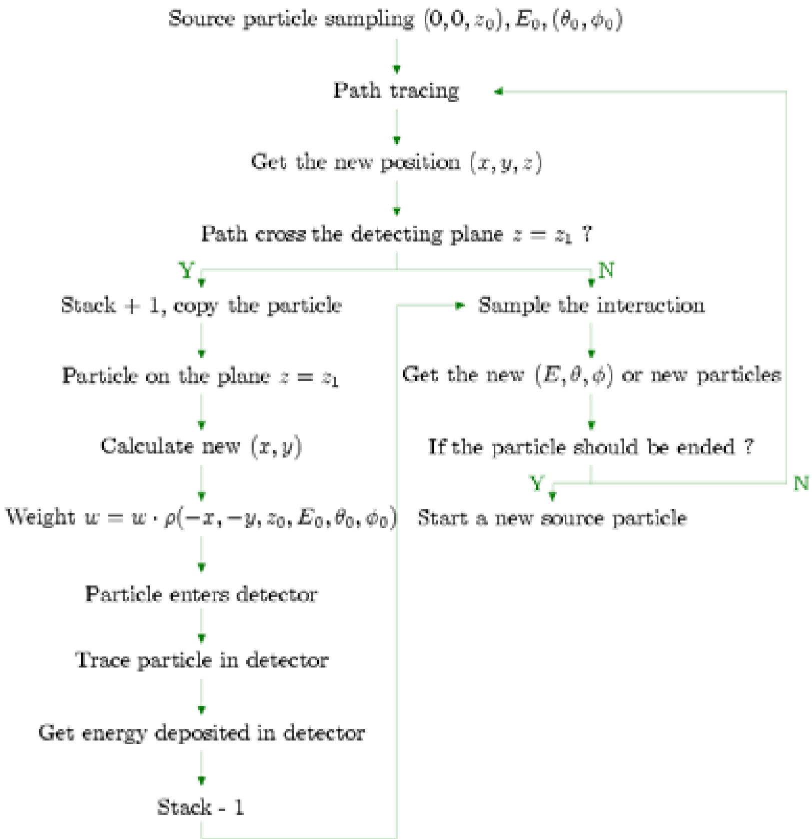

Figure 3. Flowchart of geometrical equivalent Monte Carlo simulation

Table II. The comparison of current rates of direct gamma at 1m and 100m of 4 single energy sources

Energy(MeV)	**2.615**	**1.76**	**1.46**	**0.662**
1 m	4.49	3.67	3.32	2.25
100 m	2.12	1.48	1.24	0.56

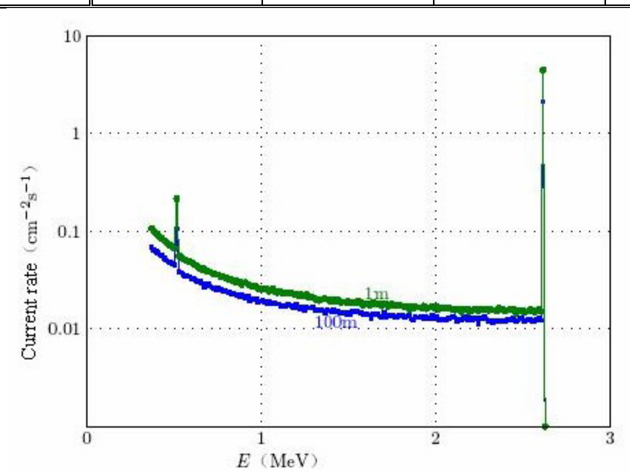

Figure 4. The current rates spectrum of 2.615Mev source at 1m and 100m altitude

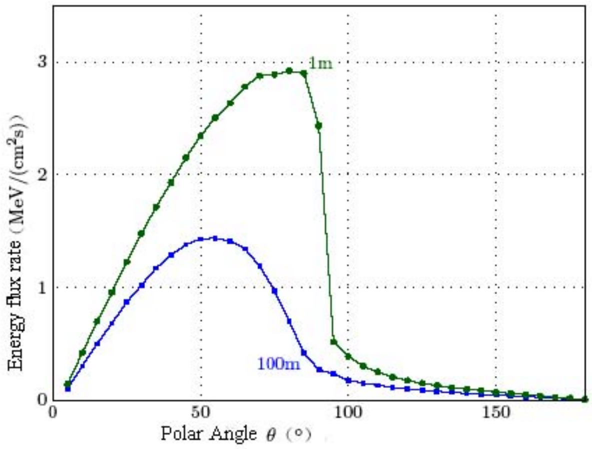

Figure 5. Comparison of angle spectrum of energy flux rates of 2.615Mev source at 1m and 100m altitude

The calculated energy spectrum of current rate of gamma ray at 100m altitude from natural source are given in Figure 6, from which the peak of electron-positron annihilation and characteristic peaks of U, Th, and K series.

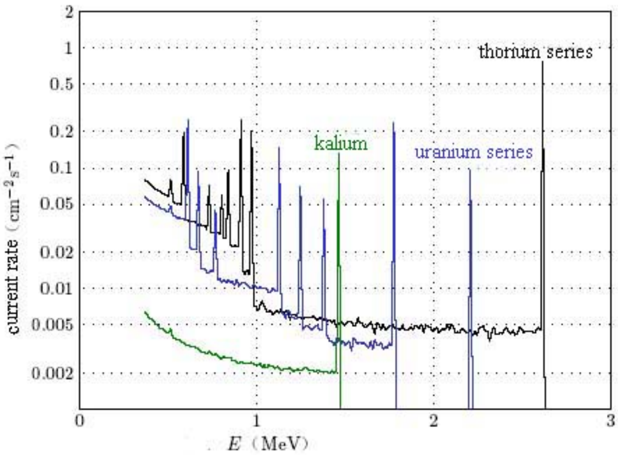

Figure 6. The spectrum of current rate of infinite uniform ground source at 100m altitude.

4.2 Monte Carlo simulation to aid calibration

Calibration is an important issue in aerial surveying. Usually, the Monte Carlo simulation is combined with experiments to obtain the results.

In ground calibration using radioactive pads, four pads are setup. Three of the pads have anomalous concentrations of K, U and Th respectively. The fourth pad acts as a background pad. Each pad, embedded in soil, is equivalent cylindrical with 6.37 meters radius and 0.5 meters height.

Measurements over concrete calibration pads and known concentrations of the radioelements, as shown in Table III, can be used to calculate the stripping ratios. Since K, U and Th spectra overlap, empirically derived stripping ratios are used to correct each elemental window count rate for the effects of the other elements.

Table III. The concentrations of the radioelements in pads

concentration	K(10^{-2})	U(10^{-6})	Th(10^{-6})
K model pad	5.60	1.18	2.42
U model pad	0.25	28.42	2.22
Th model pad	0.20	1.02	57.31
Background model pad	0.19	0.69	1.80

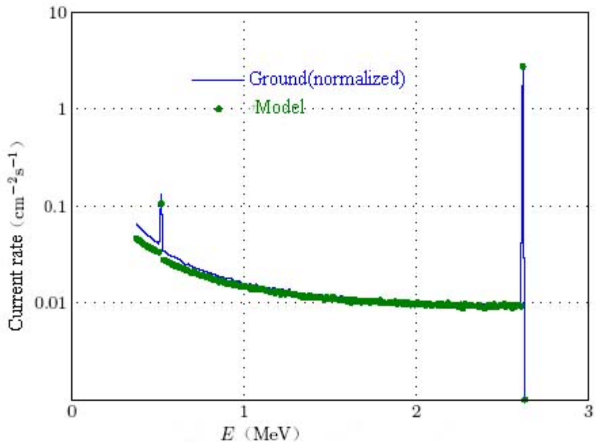

Figure 7. The spectrum of current rate at 100m altitude of 2.615MeV gamma ray from pad and infinite homogenous ground sources.

The spectrum of current rate gamma ray from pad and infinite homogenous ground sources are calculated and compared. Figure 7 shows the comparison of spectrum of current rate at 100m altitude of 2.615MeV gamma ray from pad and infinite homogenous ground sources. At lower energy, the scattering component of the pad is slightly smaller than that of infinite homogenous ground sources.

The spectrums of current (with full energy peak) at 1 meter high for each pad are calculated. And then the response spectrums of detector, where the Gaussian energy broadening of photopea ks are considered based on experiments, were simulated and compared with experimental results. Figure 8 shows the case for Th model. The simulated energy spectrum is in conformity with exp erimental results.

The stripping correction was used to correct each of the K, U and Th window count rates for those gamma rays not originating from their particular radioelement or decay series. And the cali bration factors, defined as the ratio of window counts to activity of radionuclide, have been deriv ed from Monte Carlo simulation. The calibration factors of surface Cs-137 source at different alti tude are shown in Table IV. The calculated calibration factor of surface Cs-137 source at 1 meter is accord with measured results (13.4 Bq.m-2/cps).

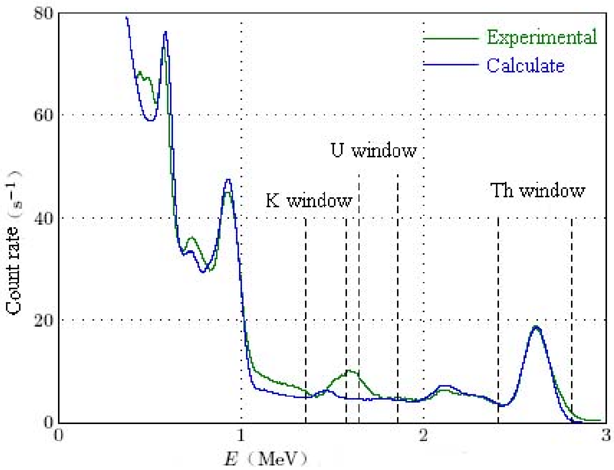

Figure 8. The simulated and experimental energy response spectrum of detector at 1 m high of Th pad model.

Table IV. The calibration factors of surface Cs-137 source at different altitude

Altitude (m)	1	50	80	100	120	150
Calibration factor ($Bq.m^{-2}$/cps)	13.3	26.9	39.5	50.5	64.1	90.1

5 SUMMARY

In this paper, the geometry equivalence method Monte Carlo method and simulation code for airborne gamma ray spectrometry were described, validated and has been applied to investigate practical airborne gamma ray spectrometry system. The airborne spectrum of gamma ray from ground source and radioactive pads sources were simulated. The response of detector was calculated. The simulated results are accord with that of experiments. The simulated results are combined with experimental data to determine calibration factors of airborne gamma ray spectrometry system and quantitatively analyze aerial measuring data.

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