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A hybrid method on sourceless sensitivity calculation for airborne gamma-ray spectrometer

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HIGHLIGHTS

- A hybrid method based on the combination of numerical calculation and Monte Carlo simulation can work efficiently.
- The result by proposed method is agreeable well with the empirical result.
- We also obtained the sensitivity of AGS to the isotopes of ^{131}I, ^{137}Cs and ^{60}Co.

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ABSTRACT

The sensitivity calculation of airborne gamma-ray spectrometer (AGS) is usually performed by on-ground or in-flight calibration. However, both methods are cost-ineffective or not permissive, especially for artificial radioisotopes with short half-lives. Alternative to these methods is the Monte Carlo simulation, which has been widely applied over the last few decades. The greatest challenge to the practicability of the Monte Carlo simulation in the AGS calibration is its low computational efficiency for ensuring an acceptable reliability. This article proposes a hybrid numerical method for the sourceless AGS calibration by combining the deterministic point-kernel approach and the Monte Carlo simulation. This method is not only more efficient than the source-based calibration by an empirical method, but also independent of the source availability for on-ground or in-flight calibration. For a given soil test model, AGS sensitivities calculated by this hybrid method agree well with those obtained from the empirical method for the in-flight calibration.

1. Introduction

Airborne gamma-ray spectrometer (AGS) has been mainly used for many years in the direct detection of ore bodies and the lithological mapping of geological surveys. Its other applications, such as the evaluation of health risks associated with radon in houses, the mapping of fallout from nuclear accidents, soil mapping, ground water discharge and salinity studies et al., have also been developed in recent years (IAEA, 2003). These applications require a sensitivity calibration for AGS to be capable of mapping distribution of radioisotopes in soil or rock over a region of interest. Most of calibration methods are empirical, either requiring on-ground calibration pads or calibration range containing both radioisotope types and content ranges of interest (Grasty and Minty, 1995; COSTIND, 2005), which could be cost-ineffective or not permissive in reality. Sourceless sensitivity calibration methods do not limit to the availability of a calibration pad or range, but rely on accurately modeling the medium geometry, property and gamma-ray transport physics by using legacy codes and their associated databases. Due to its economy, efficiency, flexibility for a variety of applications, the sourceless calibration method is attracting more and more attention from the researchers and users of AGS.

There are two types of sourceless sensitivity calibration methods for AGS. The first method is based on the deterministic numerical calculations which have been extensively studied for years. Beck and De Planque (1968), Kirkegaard and Løvborg (1974) solved the Boltzmann transport equation for a layer of uniform radioactive medium covered by the non-radioactive air. Darnley and Grasty (1971), Clark Ronald et al. (1971) and Killeen et al. (1975) constructed the radiometric profiles by a convolution of two functions, a distribution function of radioactive intensity on the ground surface and a point detector

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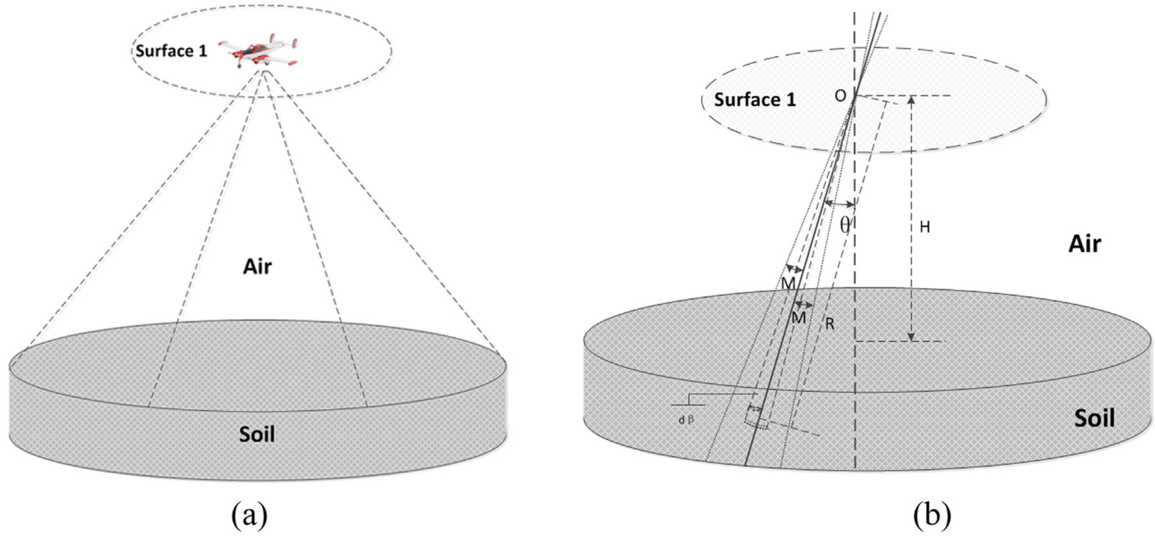

Fig. 1. The model of airborne gamma-ray detection.

Table 1
Densities and compositions of soil (Zhang et al., 2017) and air.

Materials	Element Contents (wt%)						
Soil (1.78 g/cm^3)	H	C	O	F	Na	Mg	Al
	0.140	0.030	46.736	0.080	2.838	2.096	8.154
	Si	P	S	Cl	K	Ca	Ti
	27.80	0.120	0.050	0.050	2.598	3.641	0.441
	V	Cr	Mn	Fe	Cu	Rb	Ba
	0.010	0.010	0.100	5.015	0.010	0.030	0.050
Air (0.00129 g/cm^3)		C	N	O	Ar		
		0.016	75.519	23.177	1.288		

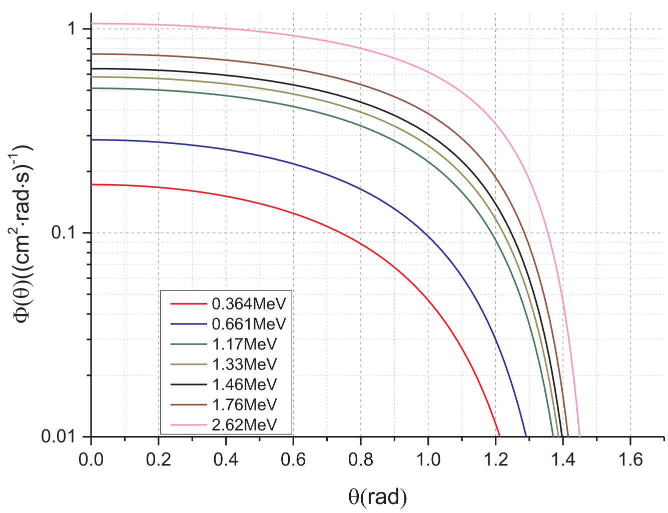

Fig. 2. The relative angular distribution of gamma-ray flux (relative to $A{\bullet}q$) for different energies at 120 m in height.

response function above the ground. Grasty et al. (1979) studied the angular effect of cylindrical detectors on the sensitivity analysis of AGS. Tewari and Raghuwanshi performed a similar angular sensitivity study on rectangular slab detectors (Minty, 1997). Billings and Hovgaard (1999) deduced the response functions of rectangular detectors with various solid angles and thicknesses for different radioactive sources. Wu et al. (2016) established a sourceless sensitivity calibration method based on the full-energy peak efficiency formula for a point source. The second method is based on the Monte Carlo simulation, which has been widely applied to the sourceless sensitivity calibration for AGS. Allyson and Sanderson (1998) developed two specific-purpose Monte Carlo codes and applied them to the sourceless sensitivity calibration for AGS. Coetzee (1999) simulated AGS gamma-ray spectra using the MCNP4B code, which were then applied to the AGS models under the simplified survey conditions. Fang et al. (2007) developed a semi-logarithm linear relationship between the lower limit of detectable ^{60}Co relative activity normalized by background radioactivity and the depth of ^{60}Co buried underground.

The deterministic numerical calculation method has advantages of simplicity, efficiency and easiness in AGS sensitivity calibration, however it's unable to reliably model the multiple Compton scattering process of gamma rays, which could be a primary component in the AGS spectra. In contrast, the Monte Carlo method can simulate all gamma-ray transport processes and generate more accurate AGS spectra, but its computational efficiency is low for ensuring the calibration quality and reliability for a large scale of source distributions. The hybrid method proposed in this paper, by combining the strengths of both deterministic point-kernel and the Monte Carlo simulation, can provide an alternative approach, efficient and reliable, to the sourceless sensitivity calibration.

2. Materials and methods

The geometric model for the hybrid method consists of two infinite subspaces divided by a flat surface, as the surface 1 which is shown in Fig. 1(a). The lower and upper subspaces are filled with soil and air, respectively. The AGS detectors are located within the upper subspace at a given height above the ground surface. The gamma-ray transport process in the lower space external to the detectors is modeled by the deterministic numerical method, which has an extremely high computational efficiency for a largely distributed but relatively simple source. To better represent the complicated gamma-ray transport process in the detector, the Monte Carlo simulation is applied to determine the AGS detector response.

As shown in Fig. 1(b), the mono-energetic gamma-ray flux $d\varnothing$ at point O, which is caused by gamma rays emitted from a volume element dV in the ground soil, is given as follows (Clark Ronald et al., 1971),

$$d\varnothing = \frac{A{\bullet}\rho{\bullet}q{\bullet}dV}{4\pi R^2} e^{-(R-H{\bullet}\sec(\theta)){\bullet}\mu_s} e^{-H{\bullet}\sec(\theta){\bullet}\mu_a} \tag{1}$$

where, A and ρ are the radionuclide activity concentration and density of the soil, respectively; q is the emission probability of the mono-energetic gamma ray; R is the distance from dV to point O; H is the height between detection surface and ground surface; μ_s and μ_a are the linear

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