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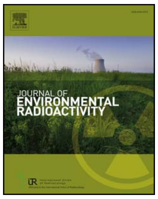

InSiCal – A tool for calculating calibration factors and activity concentrations in *in situ* gamma spectrometry

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ABSTRACT

In situ gamma spectrometry is a widely applied analysis technique for the determination of radioactivity levels in soil. Compared to traditional laboratory analysis of soil samples, *in situ* techniques offer a quick and low-cost way of obtaining accurate results from on-site measurements. However, although the technique is well-known, the dependence of *in situ* gamma spectrometry on complex and time-consuming calibration procedures as well as in-depth knowledge of the geometric distribution of the source in the ground deters many potential users from employing it in their routine work. Aiming to alleviate this issue, a software tool named InSiCal (*In Situ* gamma spectrometry Calculator) has been developed to make *in situ* gamma spectrometry more accessible to both experts and non-experts in the field. This is done by simplifying and streamlining both calibration and activity calculation through a simple and intuitive graphical user interface. Testing in real field conditions show that InSiCal is capable of yielding results which are in very good agreement with soil sample analyses, and that the results may be obtained using different detector types (HPGe, NaI, LaBr and CZT). Overall, InSiCal, provides results which are comparable in accuracy to laboratory measurements, indicating that it fulfills its purpose successfully.

1. Introduction

In-situ gamma spectrometry has been a well-known technique since its inception in the late 1960s, when it was first applied to the measurement of fallout radionuclides from nuclear weapons testing as well as of background radiation (Beck et al., 1964; Beck, 1968). The first elaborate method description published in the early 1970s (Beck et al., 1972). Early applications of in-situ gamma spectrometry were carried out using NaI(Tl) scintillation detectors, however portable HPGe gamma spectrometers for in-situ applications have been available for more than 30 years. Due to their superior resolution compared to scintillator detectors, they are now the most commonly used detector type for in-situ measurements of gamma emitting radionuclides. Further updates on method descriptions became available throughout the 1990s (ICRU, 1994; Miller and Shebell, 1995). The technique has also been included in IAEA technical reports as a technique for characterization of contaminated sites for remediation purposes (IAEA, 1998) as well as a generic procedure for monitoring following a nuclear or radiological emergency (IAEA, 1999). Applications of *in situ* gamma spectrometry vary significantly; a relatively recent overview can be found in Tyler (2008). In 2014 an ISO Guide on the measurement of in-situ gamma spectrometric measurement in soil was published, providing international guidelines on how to appropriately identify radionuclides and quantify their activity using *in situ* gamma spectrometry (ISO 18589-7:2013).

In situ gamma spectrometry is an important complement to traditional sampling and laboratory measurements because it allows for a fast and cost-effective way of performing characterization of potentially contaminated sites and localizing “hot spots”. The information obtained from *in situ* gamma spectrometric measurements may be used to facilitate the prediction of doses to the public, which allows it to potentially influence decisions on possible countermeasures in emergency situations. Compared to results obtained by sampling, *in situ* techniques are also much less affected by heterogeneities in the source activity since the effective sample volume is larger, thus potentially making the obtained results more representative for the measurement area.

However, although *in situ* gamma spectrometry as a measurement technique is generally well-known, developing the capacity to apply it in practice can be a complex and time-consuming process. This may create a theoretical barrier which prevents possible users from

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Mathematical symbols

A multitude of different nomenclatures and symbols are employed in the existing literature on in situ gamma spectrometry. In this article, the nomenclature of ISO 18589–7:2013 is used throughout, with some minor modifications. The symbols used include:

a_S	activity per unit area or mass of the source
a_K	activity of calibration source
$a(\zeta)$	activity as function of mass per unit area of the source
d	effective distance between the source and the interaction centre of the detector
E_1	1. order exponential integral function: $E_1(\alpha) = \int_1^\infty \frac{e^{-\alpha x}}{x} dx$
E_2	2. order exponential integral function: $E_2(\alpha) = \int_1^\infty \frac{e^{-\alpha x}}{x^2} dx$
G	geometry factor
k_m	relative angular response coefficient for polar angle segment m
n_b	number of background counts in a full energy peak of interest
n_g	gross number of counts in a full energy peak of interest
p	emission probability of gamma line of interest
r_{net}	net count rate in the full energy peak of interest: $r_{net} = (n_g - n_b)/t$
t	is the live time of the measurement
W	angular correction factor
z	depth in the ground
ζ	mass per unit area
β	relaxation mass per unit area
ε	detector efficiency/calibration factor
η_0	intrinsic efficiency of the detector
η_m	cross section of the detector intrinsic efficiency for photons from the polar angle segment m
ϑ_{int}	internal polar angle of the angular segment of interest
ϑ_{ext}	external polar angle of the angular segment of interest
Φ	flux density of unscattered photons of energy at the detector position
$\left(\frac{\Delta\Phi_m}{\Phi}\right)_{E,V}$	relative portion of flux density of unscattered photons of energy E in a certain polar angle segment m at the detector position, given the distribution model V
ρ_s	soil density
μ_{Air}	linear attenuation coefficient of the air
μ_S/ρ_S	mass attenuation coefficient of the soil

employing it in their work. In order to mitigate the complexity issues and make *in situ* gamma spectrometry more accessible, a software tool called InSiCal (*In Situ* gamma spectrometry Calculator) has been developed. It allows for quick and easy calculation of all necessary calibration factors as well as radioactivity concentrations from *in situ* gamma spectrometric measurements, including their measurement uncertainties. Functionality has also been included for the calculation of calibration parameters with a minimum of empirical measurements. In this work, the basic functionality and capabilities of the InSiCal software tool are presented and discussed, together with results from real applications where InSiCal was used in the field to calculate activity concentrations of different gamma emitting radionuclides.

2. Relevant theory of *in situ* gamma spectrometry

2.1. Activity determination by in situ gamma spectrometry

In situ gamma spectrometry of radioactivity in soil is performed by mounting a gamma detector on a tripod, facing downward at a typical height of approximately 100 cm above the ground. The detector is connected to a multi-channel analyzer (MCA) and portable computer with spectrum acquisition software. A measurement is carried out for an appropriate amount of time, and the resulting gamma spectrum is analyzed for one or more full energy peaks of interest. According to ISO 18589-7:2013, the activity concentration of a radionuclide in the ground can be calculated from the net area of the full energy peaks by the equation

$$a = \frac{\left(n_g - {}^{n_b}/_{t}\right)}{p\cdot\varepsilon} = \frac{r_{net}}{p\cdot\varepsilon} \tag{1}$$

Whereas the net peak count rate, r_{net}, is easily obtained from the measured spectra, and p can be retrieved from any nuclear data library such as the Decay Data Evaluation Project's recommended data (Decay Data Evaluation Project, 2014), the determination of the efficiency calibration factor is more complex. Mathematically, the detector efficiency can be expressed as the product of three separate quantities:

$$\varepsilon = \eta_0 \cdot W \cdot G \tag{2}$$

where η_0 is the intrinsic efficiency of the detector, W is a correction factor for different responses to photons imparting the detector at various angles, and G is the geometry factor. The efficiency factor requires input on both the detector's response to photons at different energies and angles of incidence, as well as knowledge or qualified assumptions about the geometric distribution of the source in the ground.

2.2. Efficiency calibration for in-situ gamma spectrometry

The purpose of detector efficiency calibration is to obtain a relationship between the output from the detector, i.e. the net count rates of full energy peaks of interest in the spectrum, to the activity concentration of a radionuclide of interest. In traditional laboratory gamma spectrometry, the sample geometry and thus the efficiency are generally well known. However, for *in situ* gamma spectrometry, the calibration factor will depend strongly on the distribution (or assumed distribution) of the radionuclide of interest in the ground, a parameter which is often not well known. In order to establish a basis for further discussion, each calibration factor component will be briefly discussed with regards to practical determination.

2.2.1. Intrinsic efficiency calibration

The calibration for intrinsic efficiency is performed by measuring one or more point sources in the direction of the axis of symmetry of the detector, with a source to detector distance of 0.5 m or greater, and with gamma lines evenly spread out over the interval 60 keV–2000 keV. According to ISO 18589-7:2013, the mathematical expression for the intrinsic efficiency at specific photon energy is given by

$$\eta_0 = \frac{\left(n_g - {}^{n_b}/_{t}\right)}{\Phi} \tag{3}$$

The uncollided flux density of the gamma line of interest at the detector effective crystal centre, Φ, is calculated

$$\Phi = \frac{a_K \cdot p}{4\pi \cdot d^2} \cdot e^{-\mu_y y} \cdot e^{-\mu_a x} \tag{4}$$

The exponential terms in equation (4) represent attenuation of the source activity in the source holder and in the air, respectively. Further details and examples on how to calculate Φ can be found in IAEA (1999).

Usually, η_0 is determined for several photon energies within the