Journal of Environmental Radioactivity 181 (2018) 70–77

Contents lists available at ScienceDirect

Journal of Environmental Radioactivity

journal homepage: www.elsevier.com/locate/jenvrad

# Assessment of the calibration of gamma spectrometry systems in forest environments

Alan J. Cresswell[a,*], David C.W. Sanderson[b], Katsuhiko Yamaguchi[c]

[a] Institute of Environmental Radioactivity, Fukushima University, 1 Kanayagawa, Fukushima 960-1296, Japan
[b] Scottish Universities Environmental Research Centre, Scottish Enterprise Technology Park, East Kilbride, Glasgow G75 0QF, UK
[c] Faculty of Symbiotic System Science, Fukushima University, 1 Kanayagawa, Fukushima 960-1296, Japan

ARTICLE INFO

*Keywords:*
Portable gamma spectrometry
Monte Carlo simulation
Forest environments

ABSTRACT

A Monte Carlo simulation was used to develop a model of the response of a portable gamma spectrometry system in forest environments. This model was used to evaluate any corrections needed to measurements of $^{137}$Cs activity per unit area calibrated assuming an open field geometry. These were shown to be less than 20% for most forest environments. The model was also used to assess the impact of activity in the canopy on ground level measurements. For similar activity per unit area in the lower parts of the canopy as on the ground, 10-25% of the ground based measurement would be due to activity in the canopy, depending on the depth profile in the soil. The model verifies that an optional collimator cap can assess activity in the canopy by repeat survey.

## 1. Introduction

Gamma spectrometry systems, either static in-situ or mobile measurements, are routinely used to determine radionuclide activity concentrations. Typically, these systems are calibrated assuming an open field geometry with laterally uniform activity concentrations and defined mass depths. However, in many situations these calibration assumptions will be invalid. Forest environments are one such example, of particular importance in Fukushima Prefecture where approximately 70% of the territory contaminated by the 2011 Fukushima Daiichi Nuclear Power Plant (FDNPP) accident is forested.

Forests present several different issues that should be considered. Differences in soil properties result in different rates of diffusion of activity down the soil column, and hence potentially different depth distributions from adjacent pasture or agricultural land. The trunks of trees shield the detector, which will reduce the count rate in a detector system compared to the same activity distribution on open ground. It is known that increasing source burial depth reduces the field of view of detectors in open ground (Tyler et al., 1996), and thus it is expected that source depth will also be a variable in the effect of forestry on detected radiation. The canopy may contain activity that can potentially be measured by the detector system.

The work presented here uses Monte Carlo simulations of a typical portable gamma spectrometry backpack system, coupled with experimental verification. The system used for this work is based on a 76 × 76 mm cylindrical (3 × 3”) NaI(Tl) detector, and is also equipped with an optional collimator cap to attenuate radiation from the canopy (Sanderson et al., 2016). The expected implications for other detector systems are discussed.

Monte Carlo methods have been used to calculate dose rates from simulated activity distributions in open field and forested environments (Clovas et al., 1999; Malins et al., 2016). These methods have also been used to simulate the spectral response of NaI(Tl) detectors, at ground level and airborne survey heights, for open field geometries (Allyson, 1994; Allyson and Sanderson, 1998; Cresswell et al., 2001; Cresswell and Sanderson, 2012). The work presented here expands on these earlier simulations, to simulate the spectral response of NaI(Tl) detectors to the more complex geometries presented by forest environments.

## 2. Methods

### 2.1. SUERC portable gamma spectrometer

The system used here comprises a 76 × 76 mm NaI(Tl) detector with digital spectrometer and integrated GPS receiver. This system has been used for the evaluation of remediation in forests in Fukushima Prefecture (Sanderson et al., 2016; Cresswell et al., 2016), and the calibration has been validated against known open field reference sites in the UK and Japan (Cresswell et al., 2013; Sanderson et al., 2013). A collimator, consisting of a plastic (nylon-6) 200 mm diameter and 150 mm height cylinder, with a 125 mm diameter and 100 mm depth central well, has been produced to attenuate radiation from above the

* Corresponding author. Present Address: Scottish Universities Environmental Research Centre, Scottish Enterprise Technology Park, East Kilbride, Glasgow G75 0QF, UK.
*E-mail address:* alan.cresswell@glasgow.ac.uk (A.J. Cresswell).

http://dx.doi.org/10.1016/j.jenvrad.2017.10.019
Received 20 July 2016; Received in revised form 30 October 2017; Accepted 30 October 2017
0265-931X/ 

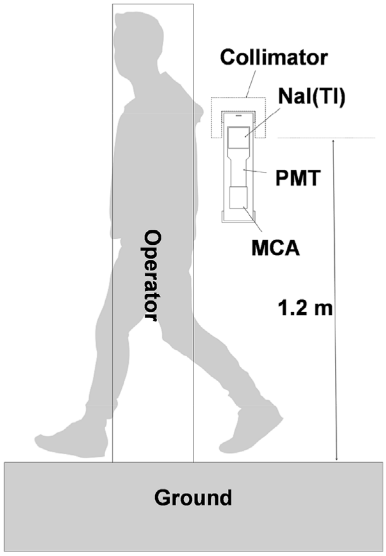


**Fig. 1.** Schematic of the backpack system consisting of a NaI(Tl) crystal with photomultiplier (PMT) and digital multi-channel analyser (MCA) in a weather proof canister, and optional collimator (dashed line). The centre of the crystal is at a height of approximately 1.2 m. For the simulation, a cuboid shaped operator is used (Buchanan et al., 2016).

detector. The system is shown schematically in Fig. 1. Angular response measurements in laboratory conditions using a $^{137}$Cs (662 keV) source predict that this collimator attenuates 42% of radiation from above, and 22% of radiation from the ground in open field conditions (Sanderson et al., 2016; Buchanan et al., 2016).

### 2.2. Monte Carlo simulations

A Monte Carlo simulation of this detector system has been developed using GEANT4 (Agostinelli et al., 2003; Allison et al., 2006) (version 4.10.0 p-02, using the G4EMLOW 6.35 library). The model has been validated by reproducing the response of a naked 76 × 76 mm NaI (Tl) detector described in the literature (Heath, 1964), and the angular response measurements for the backpack system with and without the collimator (Sanderson et al., 2016; Buchanan et al., 2016).

For the simulation of the Heath (1964) measurements a detector matching the description was used. For the backpack simulations the detector configuration matched the specifications of a Scionix Type 76 B 76 detector (http://scionix.nl/standard2.htm). The photomultiplier base unit including high voltage supply and digital spectrometer was matched to the Ortec digiBASE™ specification (http://www.ortec-online.com/download/digiBASE.pdf). These are detailed in the supplementary material, along with the external plastic canister, foam inserts, geographic positioning system (GPS) and collimator.

A simplified generic forest was modelled, shown schematically in Fig. 2. The physical properties of trees vary considerably between different species and environments. Pettersen (1984) lists the composition of dry wood from various species as consisting of 65–75% carbohydrates (cellulose and hemicellulose), 18-35% lignin and 4-10% of minor components. Nilklas and Spatz (2010) tabulate greenwood (50% water) densities for heartwood and sapwood, at 400-700 kg m$^{-3}$ for most species, with conifers having lower densities. The model consists of trees with 50 cm diameter cylindrical trunks, composed of 35% cellulose, 15% lignin and 50% water (by mass) and a density of 400 kg m$^{-3}$. The canopy is defined as a cubic volume on top of the trunks and extending half a tree spacing beyond the simulated forest, and consists of a uniform mixture of 50% air, 40% leaf and 10% wood (by volume), with the leaves a mixture of 50% water and 50% cellulose (by mass) with a density of 250 kg m$^{-3}$. Two geometries were simulated, a low canopy with a base 2 m above the ground and a high canopy with a

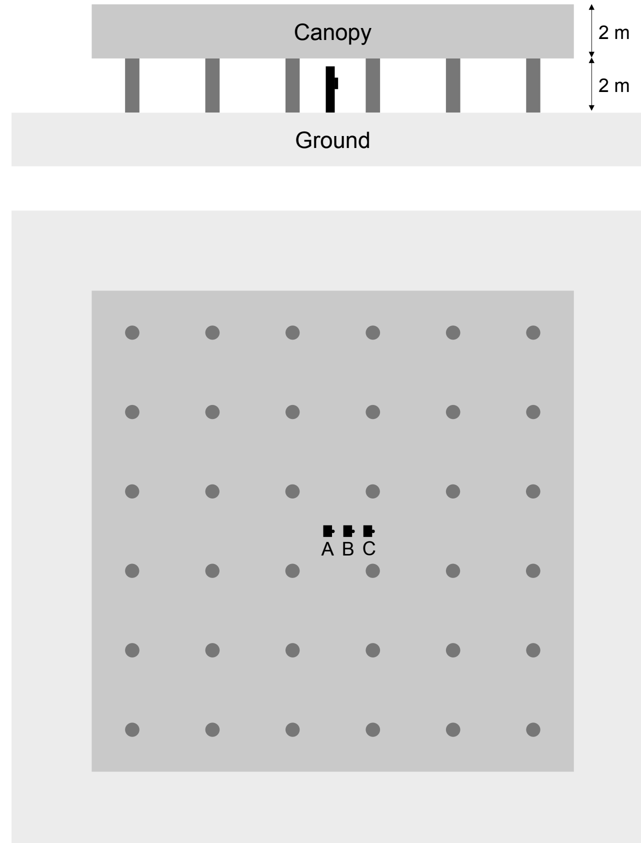


**Fig. 2.** Schematic of simplified forest geometry, with a low canopy, showing three detector positions (A, B and C) used. Simulations with a high canopy (base 4 m above ground and 10 m height) have also been conducted.

base 4 m above the ground. A canopy base less than 2 m above the ground is common for Japanese cedar and many other species commonly found in Japanese forests. The simulation modelled 36 trees placed in a square pattern with spacings between the trunks variable, for the work presented here two different trunk spacings of 2 m and 3 m were used, corresponding to stand densities of approximately 2500 ha$^{-1}$ and 1000 ha$^{-1}$ respectively. The soil is of the composition described by Beck et al. (1972); density 1600 kg m$^{-3}$ with major elemental composition 26.2% Si, 5.9% Al, 2.6% Fe, 24.4% Ca, 0.9% H, 1.0% C, and 39.0% O. (oxide mass fractions: 67.5% $SiO_2$, 13.5% $AlO_3$, 10% $H_2O$, 4.5% $Fe_2O_3$, and 4.5% $CO_2$). It is recognised that the soil composition of forests, especially the litter and humic layers, will differ in composition and density from this. However, to first approximation, the mass attenuation coefficients for gamma radiation with energy > 200 keV has been shown to be independent of composition (Cresswell and Sanderson, 2012). If activity profiles are expressed in terms of mass depth then the effect of density variation in the soil column is also accounted for. These materials are also described in more detail in the supplementary material.

Simulations were conducted for different source distributions. For activity on the ground, the simulations were conducted for uniformly distributed layers of zero thickness and 25 m radius at different linear depths, from which different depth distributions can be estimated by summing the outputs of each depth simulation. For activity in the canopy, the simulations were conducted for activity uniformly distributed in volumes of the canopy of thicknesses of 0.2 and 1.0 m. The counts in the full-energy peak in the simulated spectra were normalised to count rates per unit kBq m$^{-2}$ (for activity on the ground) or per Bq m$^{-3}$ (for activity in the canopy). Simulations of activity in the soil were repeated with the trees removed to allow comparison with the open field