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The validation of synthetic spectra used in the performance evaluation of radionuclide identifiers

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HIGHLIGHTS

- A validation of synthetic data created in order to evaluate radionuclide identification systems has been carried out.
- Statistical analysis has shown that the data accurately represents experimental data.
- A limit to the amount of data which could be created using this method was evaluated.
- Analysis of the synthetic gamma spectra show identical results to analysis carried out with experimental data.

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ABSTRACT

This work has evaluated synthetic gamma-ray spectra created by the RASE sampler using experimental data. The RASE sampler resamples experimental data to create large data libraries which are subsequently available for use in evaluation of radionuclide identification algorithms. A statistical evaluation of the synthetic energy bins has shown the variation to follow a Poisson distribution identical to experimental data. The minimum amount of statistics required in each base spectrum to ensure the subsequent use of the base spectrum in the generation of statistically robust synthetic data was determined. A requirement that the simulated acquisition time of the synthetic spectra was not more than 4% of the acquisition time of the base spectrum was also determined. Further validation of RASE was undertaken using two different radionuclide identification algorithms.

1. Introduction

Radionuclide Identification Devices (RIDs) are a class of radiation detection instrumentation of increasing importance to security applications. Improving the technical means of RIDs to identify radionuclides contributes to international efforts to counter the threat of nuclear terrorism. Recent focus areas for research and development into RIDs include the evaluation of existing commercially available systems (Beck, 2000; Blackadar, 2004), the development of new front end detector materials (Carchon et al., 2007) and the development of new identification algorithms for interpreting gamma-ray spectra (Boardman and Flynn, 2012; Boardman et al., 2012; Owsley et al., 2009).

International performance standards, such as the ANSI N42.34 standard (2007a), provide a specification of the minimum requirement for RID performance. Minimum levels of performance are established based on a library of 18 radionuclide sources with an additional heightened level of performance associated with a further 9 radionuclide sources provided as a recommendation. The specification requires that a RID be capable of identifying a particular radionuclide in 8 out of 10 trials. Although an evaluation to determine the limits of a system requires a substantially larger data library than that required to determine the compliance with international standards.

Determining which technologies to progress towards commercial readiness in a timely manner is an important requirement of industry (Beck, 2000). Proper evaluation of RIDs requires the generation of substantial amounts of experimental data associated with the large number of radionuclides of interest and the large variety of conceivable operating scenarios in which the various radionuclides might be found.

For example, 100 trials of 60 s spectra result in a data collection time of 1.6 h for each radionuclide of interest. Furthermore, system evaluation requires data at a variety of different dose rates and must also include scenarios involving two or three radionuclide source combinations. A complete evaluation of all possible scenarios required to demonstrate compliance with the standard or determine detection limits can take months of data collection, which is prohibitively long. At the same time a reduction in the

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amount of data collected and the number of scenarios to which the RID is evaluated risks the introduction of unquantified system vulnerabilities, potentially compromising the usefulness of the RID for national security purposes.

To assist in this evaluation the IAEA have established the Replicative Performance Assessment of Spectroscopic Equipment (RASE) exercise as part of a coordinated research project (CRP) entitled IAEA CRP M22.007 '*Development and implementation of instruments and methods for detection of unauthorized acts involving nuclear and radioactive material*'. This exercise is designed to provide an independent and objective performance assessment of commercial RIDs. RASE (2009) is based on a Monte Carlo approach that uses experimentally acquired gamma-ray spectra, with excellent counting statistics, as a probability distribution function from which lower statistical sample spectra are created (Arlt et al., 2009). The initially acquired experimental spectrum is referred to as the base spectrum. Depending on the amount of counts in the base spectrum each subsequent synthetic sample can be created in a matter of seconds and entire data libraries can be created in a matter of hours. The RASE system is important not just for the purposes of evaluating emerging RID technology but also for the evaluation of existing RID systems to assist in determining where future work could be directed for the purpose of technology improvement.

An alternative approach to create synthetic gamma spectra would be to produce spectra from a full system based Monte Carlo simulation. A variety of programs are available which use Monte Carlo methods to model a user defined detector system, shielding arrangements and source configuration to simulate experimental data collection, for example Chen and Wei (2008). Although a simulation of the entire system set up is conceivable it usually requires simplification as a trade off with the time required to run the simulation (Thoreson and Schneider, 2010). These more comprehensive simulations tend to be useful in the development stage of instrument design before a physical detector system exists (Robinson et al., 2006).

To date the RASE sampler has not been comprehensively validated using experimental data (Arlt et al., 2009).To ensure that the synthetic spectra are equivalent to an experimental based evaluation approach, it is important to validate that the synthetic spectra have the same statistical behaviour and the same response from identification algorithms as experimentally obtained spectra. In this paper the response of RASE synthetic spectra and experimental spectra at a variety of different dose rates has been analysed. The statistical behaviour, of the synthetic and experimental spectra, from a large number of repeated trials has been analysed. The effect of base spectrum counting statistics has also been investigated to determine how long a base spectrum should be acquired for a particular dose rate. The RASE sampler tests the software aspect of the RID and assumes for this study that there will be no changes due to hardware failures or drift due to environmental changes during use.

2. RASE sampler theory

2.1. Sampling

The RASE sampling program uses a semi-empirical approach to create a large data library of gamma-ray spectra which can subsequently be used to evaluate the identification performance of a RID. The RASE sampler uses experimental data as a basis to create gamma spectra which have a user defined acquisition time, dose rate and radionuclide mixture. To produce synthetic spectra of a single radionuclide the RASE software requires two inputs, an experimentally obtained gamma-ray spectrum acquired over a sufficiently long period of time which has been background subtracted (known as a base spectrum) and a sensitivity parameter in units of cps/μSv/h which has been experimentally measured for a variety of gamma-ray dose rates. These two parameters capture the unique detector response from which synthetic gamma-ray spectra can be created. Where required the base spectrum of background can also be inputted into RASE in the same manner.

To utilise RASE to produce a synthetic gamma-ray spectrum the user first selects a radionuclide from a list of available base spectra then sets the dose rate for that radionuclide and the acquisition time. The software uses the set time T and dose rate $H_i^*(10)$ along with the sensitivity parameter φ_i, to calculate the amount of counts I which will be in the sample spectrum as shown in (1).

$$I = \varphi_i H_i^{(*)}(10) T \tag{1}$$

The base spectrum is used to produce a probability distribution function $N(x)$ and define a co-ordinate system within which random numbers are generated. To create a sample spectrum $S(x)$ a co-ordinate (a,b) is generated from a random number generator, $a \in [0, A_{max}]$ and $b \in [1, B_{max}]$. Here A_{max} is the number of channels in a spectrum and B_{max} is the maximum number of counts in a channel. If b is greater than $N(a)$ then the co-ordinate is rejected. Otherwise, if b is less than $N(a)$, $S(a)$ will be incremented. This process is repeated until the following condition is met (Arlt et al., 2009):

$$I = \sum_x S(x) \tag{2}$$

2.2. Combining radionuclides

The RASE sampler can be used to create gamma-ray spectra for combinations of radionuclides. The creation of mixed gamma spectra assumes that individual spectral components are distributive and as such the combined spectrum is the arithmetic sum of the individual components shown in (3). $N_\Sigma(A)$ is the combined gamma-ray spectrum, $N_\Phi(A)$ and $N_\Psi(A)$ are the gamma-ray spectra of the individual radionuclides and $G(E,A)$ is the instrument response function with $\Phi(E)$ and $\Psi(E)$ being the response to each radionuclide respectively.

$$N_\Sigma(A) = \int (\Phi(E) + \psi(E)) G(E,A)\, dE = N_\Phi(A) + N_\Psi(A) \tag{3}$$

This allows the user to define the composition of the synthesised gamma spectra.

3. Evaluation of synthetic spectra

This validation will evaluate data sets which are typical of an evaluation of a RID system. An evaluation typically aims to determine the detection limits of a system or to verify performance at dose rates specified in international standards. The largest data set required to ensure that a detection system meets international standards is a set of 1000 trials used to determine the system false alarm rate to background radiation in the ANSI N42.38 (2007b) standard for spectroscopic radiation portal monitors. The data used for this evaluation was limited to the data required to evaluate an identification system.

The key factors which were used to determine if the RASE synthetic spectra were statistically equivalent to experimental data are

(1) The synthetic data should accurately represent a mixed radiation field and be able to reproduce changes in dose rates.
(2) The variation in a single channel from a large number of synthetic spectra should have the same statistical distribution