Journal of Environmental Radioactivity 177 (2017) 225–232

Contents lists available at ScienceDirect

Journal of Environmental Radioactivity

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

A rotating-slit-collimator-based gamma radiation mapper

Jonas M.C. Nilsson, Robert R. Finck, Christopher L. Rääf*

Medical Radiation Physics, Department of Translational Medicine, Lund University, Skåne, University Hospital, S-205 02 Malmö, Sweden

ARTICLE INFO

Article history:
Received 28 July 2016
Received in revised form
4 July 2017
Accepted 5 July 2017

Keywords:
Gamma radiation
Collimator
Image reconstruction
HPGe
Deconvolution
Mapping

ABSTRACT

For situations with radioactive material out of control where it may be physically difficult or prohibited to access areas close to the source, measurements from distance may be the only way to assess the radiation environment. Using collimated detectors will provide means to locate the direction of the radiation from the source. To investigate the possibilities of mapping gamma emitting radioactive material in a closed non-enterable area, a tentative system for mapping radioactive materials from a distance was built. The system used a computer controlled cylindrical rotating slit collimator with a high purity germanium detector placed in the cylinder. The system could be placed on a car-towed trailer, with the centre of the detector about 1.4 m above ground. Mapping was accomplished by the use of a specially developed image reconstruction algorithm that requires measurements from two or more locations around the area to be investigated. The imaging capability of the system was tested by mapping an area, 25 by 25 m^2, containing three 330 MBq ^{137}Cs point sources. Using four locations outside the area with about 20 min measuring time in each location and applying the image reconstruction algorithm on the deconvoluted data, the system indicated the three source locations with an uncertainty of 1–3 m. The results demonstrated the potential of using collimated mobile gamma radiometry combined with image reconstruction to localize gamma sources inside non-accessible areas.

1. Introduction

A common way to survey an area for gamma emitting radioactive material is to use a movable detection instruments within that area. It can be done by mounting the detectors on backpacks for surveys on foot (Bernhardsson et al., 2015; Cresswell and Sanderson, 2012; Nilsson et al., 2014), in vehicles (Hjerpe et al., 2001; Tanigaki et al., 2013) or in airborne systems (Kock and Samuelsson, 2011; Tyler, 2008). In recent years there has also been a significant development in the use of unmanned remote controlled vehicles in sampling and measuring radiation fields (Schneider et al., 2015). Instruments in movable detection are usually GM-, NaI(Tl)-, LaBr3(Ce)- or HPGe-detectors. They are typically used without shielding or collimation, rendering the instruments insensitive to the direction of the radiation field. The localization of sources is based on the relationship between the photon fluence rate and the distance from the source, where the sharp increase in fluence rate when approaching a source is exploited to pinpoint its location. By making a large number of measurements and pairing them with geographical coordinates it is possible to create maps indicating the distribution of radioactive material in the surveyed area (Aage et al., 2009; Kock et al., 2014; Minty, 2011; Panza et al., 2015).

There can be a number of reasons that the area to be surveyed cannot be entered, such as suspected presence of explosives or fire hazards, dangerously high radiation levels, forensic procedures limiting access, the need to make under cover operations, or just structures that physically prevent access. In these cases the method with movable detectors is more difficult to apply because of the necessary larger distances to potential sources. However, detectors with directional sensitivity, for example pinhole-collimated detectors can in these situations be used to identify directions to radiation sources. By measuring at different positions outside the restricted area, the location of a source can be determined if it is strong enough to produce a detectable signal above the background (Durrant et al., 1999; Fujimoto, 2006; Kronenberg et al., 1996; Redus et al., 1992; Volkovich et al., 1995). Another directional sensitive method using a rotating modulation collimator to detect sources from only one measurement position has been described by Kowash (2008).

The principle of directional detection is further investigated in this study using a sensitive HPGe-detector aimed for low level

---

* Corresponding author.
E-mail address: Christopher.Raaf@med.lu.se (C.L. Rääf).

http://dx.doi.org/10.1016/j.jenvrad.2017.07.007
0265-931X/© 2017 Elsevier Ltd. All rights reserved.

gamma spectrometry together with heavy shielding to facilitate its use in a high radiation level environment. The aim was to build and study the qualities of a proof of concept system that could be capable of mapping the locations of gamma emitting radioactive sources in a limited area when it is not possible or desirable to enter the area with radiation detectors on foot, in vehicles or air-borne. The system that was built uses a rotating slit collimator around the sensitive volume of the detector. It can perform an angular scan of the radiation field. By scanning the field from two or more positions and applying an image reconstruction algorithm, a fluence intensity map can be produced that shows possible locations of gamma radiation sources. The detection equipment, data processing technique and the result from test measurements are described below.

2. Materials and methods

2.1. System description

The system uses a tube-formed, slit-opening collimator over the sensitive volume of a high purity germanium (HPGe) detector. The collimator surrounding the detector is placed on a rotating jig, driven by an electric motor, which rotates the collimator (and thus its slit opening) in the horizontal plane. The angular direction of the slit is controlled by a computer connected to an electronic pulse counter on the electric motor, producing 469k pulses per revolution of the collimator. A simple sight, consisting of two vertically mounted needles, is placed on top of the collimator, which enables calibration of the directional setting of the slit opening against a reference point in the terrain. This is needed for determining the exact rotation angles, which together with the measured photon fluence are used in the image reconstruction algorithm. A schematic view of the system is provided in Fig. 1.

The collimator parts have been cast from the alloy Roses metal (50% Bi, 25% Pb and 25% Sn by weight), which has a melting point of about 100° C. It was used because it provides high attenuation while at the same time being soft and easily malleable. The resulting cast was then machined. The insets in the slit of the collimator (see Fig. 1 c) were milled from lead ingots. The collimator has an inner diameter of 124 mm and a thickness of 45 mm. This thickness was chosen to enable the use of the system in a high-dose-rate environment, for which it had been originally designed (Jönsson, 2010). The slit opening in the collimator can be widened or narrowed by changing the slit insets. Different slit openings were tested. For this study the opening was chosen to 11°, which is a trade-off between angular resolution and counting efficiency of the primary photon fluence reaching the sensitive part of the detector from a source in the direction of the slit opening. With this set-up the collimator reduced the detector count rate for photons incident in the slit direction down to about 1/10.

The HPGe detector used in this study was a GEM100-S p-type, coaxial detector (EG&ORTEC, Oak Ridge, USA), with a relative efficiency of 123% (IEEE Standards Board, 1987). The outer diameter of the detector was 114 mm leaving a gap of 5 mm between it and the inner wall of the collimator. The pulse height distributions from the electronics package, a DigiDART MCA (EG&ORTEC, Oak Ridge, USA), were collected by a laptop computer. A GPS receiver of type CFX-750 (Trimble, Sunnyvale, USA) with a positioning uncertainty of about 0.2 m (when using EGNOS) was used to determine the location of the system in the field. The GPS antenna was placed directly above the detector.

A special stand was built to hold the HPGe detector and the rotation mechanism with the collimator. The total weight of the system, excluding the power supply and the GPS receiver, is approximately 140 kg. For all measurements described in this work the centre of the sensitive volume of the detector was 1 m above the ground. The whole equipment can be mounted on a car-towed trailer, placing the centre of the detector about 1.4 m above ground. The rods supporting the cover over the trailer can be removed on one side, so there is no equipment material in the line of sight between the rotating collimator slit and the area to be scanned within an angle of 120°. Measurements can also be made with the cover down for situations with bad weather or to avoid exposure of the measuring equipment if it is unsuitable for the mission. The weight of the cover, 0.6 kg/m^2, only affects the photon fluence slightly. A photograph of the equipment on the trailer is shown in Fig. 2.

The electronic control unit with an electric motor that drives the rotation of the collimator, the detector electronics and the GPS receiver are connected to a laptop computer. Data collection is controlled by an application on the computer. It sends collimator orientation commands to the motor control unit, followed by a start measurement command to the HPGe-detector electronics. After the preset acquisition time has passed, a stop measurement command is sent. The collected spectral data for each angular measurement is stored on the computer for post-processing together with relevant metadata such as live-time, real-time, collimator angle, position etc. The full energy peak areas representing the radionuclides detected in the scanned area are proportional to the primary fluence rate from the direction of the collimator opening. The primary fluence rate and its direction represent the presence of a radioactive source in that direction, but in order to determine the exact location of the source, additional data processing is required as described below. In this work the fluence rate has only been used for calculation of source locations, and not for determining their activity.

2.2. Data processing and image reconstruction

By using the angular measurement sets from two or more positions around an area containing gamma emitting sources, it is possible to build an image of the source distribution in the area. An iterative reconstruction algorithm based on maximum likelihood-expectation maximization (MLEM) has been used in this study. The algorithm was originally developed for medical imaging in emission and transmission tomography (Shepp and Vardi, 1982). A rough description of the algorithm follows:

1. Start with an assumption of the distribution of radioactive material in the area of interest (in this work a uniform source distribution was assumed).
2. Simulate the measurements of the assumed source distribution at positions and angles corresponding to those of the real measurements.
3. Compare the simulated measurements with the actual measurements by dividing the curve of the actual measurement with the curve from the simulated measurements.
4. Multiply the comparison by a scaling factor and back project the result onto a new assumption.
5. Go to step 2.

This algorithm does not directly compensate for the number of measurement positions used; thus the back-projection curves have to be multiplied by a factor to modify their amplitude. This is done in step 4. The value of the factor is found by an iterative least-squares method that modifies the back-projection factor until the current guess produces simulated measurements with minimal deviation from the actual measurements.

An accurate initial assumption of the distribution of radioactive material in the area of interest is not important for obtaining the