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Investigation of three-dimensional localisation of radioactive sources using a fast organic liquid scintillator detector

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ABSTRACT

In this paper we discuss the possibility of locating radioactive sources in space using a scanning-based method, relative to the three-dimensional location of the detector. The scanning system comprises an organic liquid scintillator detector, a tungsten collimator and an adjustable equatorial mount. The detector output is connected to a bespoke fast digitiser (Hybrid Instruments Ltd., UK) which streams digital samples to a personal computer. A radioactive source has been attached to a vertical wall and the data have been collected in two stages. In the first case, the scanning system was placed a couple of metres away from the wall and in the second case it moved few centimetres from the previous location, parallel to the wall. In each case data were collected from a grid of measurement points (set of azimuth angles for set of elevation angles) which covered the source on the wall. The discrimination of fast neutrons and gamma rays, detected by the organic liquid scintillator detector, is carried out on the basis of pulse gradient analysis. Images are then produced in terms of the angular distribution of events for total counts, gamma rays and neutrons for both cases. The three-dimensional location of the neutron source can be obtained by considering the relative separation of the centres of the corresponding images of angular distribution of events. The measurements have been made at the National Physical Laboratory, Teddington, Middlesex, UK.

1. Introduction

The generation of electricity in nuclear power stations and from the use of radioactive materials in nuclear industry, medicine, military nuclear programmes and research produce radioactive wastes. The removal of radioactive materials from nuclear facility, at the end of their working life, requires radiation detection and localisation. Fast and effective decommissioning is essential to the public acceptance of nuclear technology and will help to support new nuclear build. Also, the illicit transport of radioactive materials demands that precise radiation screening techniques and instrumentation are in place [1].

Over the last 20 years, largely as a result of requirements in nuclear decommissioning and security, several gamma-ray imaging systems have been introduced and are commercially available; CARTOGAM, RadScan, RadCam and Gamma-Visor are a few examples for such gamma-ray imaging systems [2–7]. However, all these gamma-ray imaging systems are only able to locate radioactive sources in a two-dimensional domain. Also, images produced by these systems cannot distinguish a neutron source from a gamma source, as gamma rays always accompany neutron production and fast neutron scintillants that respond to both are usually necessary. Especially in security applications, such a scenario could activate an alarm and has the potential for causing operational disturbance. Therefore, the user needs to carry out further measurements and analysis to determine whether or not the located source is a neutron source.

Most neutron imaging techniques are based on radiography, transmitting a beam through an object onto a detector. The use of fast organic liquid scintillators became popular in radiation detection and location applications as a result of recent advances in digital pulse-shape discrimination methods [8–12] and demanding requirements in security applications associated with ^{3}He replacement [13,14]. Recently, a fast organic liquid scintillator-based mixed radiation imaging system has been reported where images were produced for both neutron and gamma-ray components [15,16]. Most importantly this system can discriminate a gamma source from neutron source using a single detector even if they are co-located. However, this system is also only capable of locating sources in two-dimensional domain. In this paper we are investigating a new approach to locate radioactive sources in three dimensions.

2. Experimental method

The detector was placed inside a heavy tungsten collimator which was then mounted on an equatorial mount (Fig. 1). The

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Fig. 1. The imaging system used in this research with the heavy tungsten collimator, fast organic liquid scintillator detector, bespoke fast digitizer and an equatorial mount.

mount was connected to a personal computer through a serial port. The detector output was connected to a bespoke fast digitizer and the output of the digitizer connected to the computer through an Ethernet connection. The operation of the digitizer and the mount was synchronised and automated using the MATLAB instrumentation and control tool box.

The imaging system detector consists of an EJ-301 organic liquid scintillator, which is a 4 ml small volume cylindrical cell (Scionix, The Netherlands). The scintillator is attached via a light guide to a Hamamatsu R5611 photomultiplier tube (operating voltage is -840 V DC). Inside the collimator, the detector axis is placed in coincidence with the axis of the collimator. The heavy tungsten collimator (TAM 3950: it is a tungsten alloy grade with 95% W, 3.5% Ni, 1.5% Fe) has an outside diameter of 57 mm, 10 mm thickness and 250 mm length and has a mass of 6.6 kg. It has a field of view of 22° at the front of the detector and reduces the portion of radiation penetrating from outside the field of view. The digitizer (Hybrid Instruments Ltd., Lancaster, UK) is especially designed to process the pulses from organic liquid scintillator detectors and can take samples at up to 500 MHz. Each pulse shape consists of 128 sample values taken at 2 ns intervals, at an amplitude resolution of up to 12 bits.

A neutron source (americium beryllium source: National Physical Laboratory reference AMN 1000/1095, current neutron emission rate is $2.372 \times 10^6\ s^{-1}$) has been attached to a vertical wall as shown in Fig. 2. The scanning system (Fig. 1) was then placed and the data were collected from a grid of measurement points for both cases individually. In the first case, the scanning system was placed a couple of metres away from the wall and in the second case, it was moved a few centimetres from the original location (case 1), parallel to the wall (Fig. 2). In each case, data were collected from a grid of measurement points (set of azimuth angles for set of elevation angles) which covered the source on the wall.

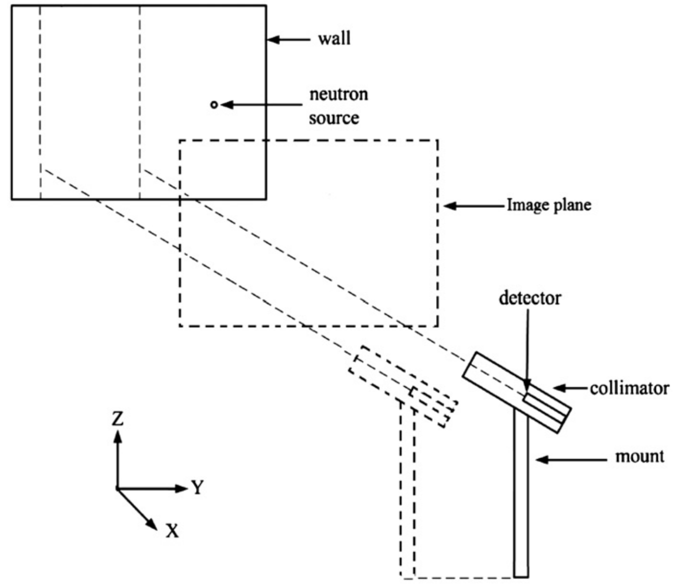

Fig. 2. Schematic of the experimental set-up; images have been produced in an arbitrary plane (image plane) shown in the figure.

3. Results

The discrimination of fast neutrons and gamma rays detected by the scintillator detector is carried out on the basis of the differences in the decay portion of the pulse. The discrimination of these different radiation types is well established in the digital domain and a pulse gradient analysis of neutron and gamma discrimination was used [8,9]. It is based on the peak amplitude and the amplitude of the pulse at a fixed time after the peak amplitude. Scatter plots of discrimination amplitude versus peak amplitude have been produced for each case at the position of maximum count detection, where Fig. 3(a) corresponds to case 1 and Fig. 3(b) corresponds to case 2. On the basis of an earlier calibration of the detector, neutrons correspond to the events in the upper plume and gamma rays correspond to the events in the lower plume in these plots.

Spatial distributions have been produced for both cases in an arbitrary image plane, where detector to the arbitrary image plane distance is known. Total counts due to the AmBe (americium beryllium) source are shown in Fig. 3(c) (case 1) and Fig. 3(d) (case 2). The corresponding neutron counts are also shown in Fig. 3(e) (case 1) and Fig. 3(f) (case 2). Spatial distributions have also been produced for a gamma source (^{137}Cs) for both cases and are shown in Fig. 4(a) (case 1) and Fig. 4(b) (case 2). The scale on the colour map corresponding to the number of counts recorded as a function of position shown in the figures adopts the same sequence as the visible colour spectrum. These images clearly indicate the two-dimensional location of the source in the arbitrary image plane. The three-dimensional location of the source can be found trigonometrically, considering the relative separation between centres of case 1 and case 2 (for total counts or neutrons) and the separation between the detector and the arbitrary image plane.

4. Discussion and summary

The relative locations of the scintillator centre position and the locations of neutron source (in an arbitrary image plane) can be expressed in terms of Cartesian coordinates as shown in Fig. 5 (the base of the mount is defined as the origin (0, 0, 0) of the