A gamma-ray imaging camera for NORM radioactivity detection

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Abstract. Naturally occurring radioactive materials (NORM) and technologically enhanced naturally occurring radioactive materials (TENORM) consists of materials enriched with radioactive elements, found in the environment, with concentrations over the ambient natural radioactivity average, such as industrial wastes and extraction byproducts. We designed a camera for gamma-ray imaging and radionuclide identification based on the coded mask technique. The camera proposed is a compact, lightweight instrument, ideal for real-time analysis, with a low power consumption, suitable for industrial process and ambient monitoring. We built a prototype consisting in 16 CsI(Tl) scintillators coupled to photo-multiplier tubes (PMTs) with a digital readout. We used a $7 \times 7$ mask composed by transparent and opaque tiles to encode radioactive gamma-rays sources image and use a reconstruction algorithm for decoding. The system was first tested using free gamma-ray radioactive sources placed at a fixed distance from the mask and than, the same sources, was placed inside an industrial nuclear waste drum to test shielding and detection limit. We will also show the results with a NORM igneous rock sample and we will try to identify the radioactive sources after a estimation of the count rate over the background, the test was carried out in lead chamber to shield the natural laboratory background. The performance of the prototype camera in terms of energy and spatial resolution with respect the detection time will be shown.

1. Introduction

Naturally occurring radioactive materials (NORM) are materials which may contain any of the primordial radionuclides or radioactive elements as they occur in nature, such as radium, uranium, thorium, potassium and their radioactive decay products, that are undisturbed as a result of human activities. Furthermore, the technologically enhanced NORM, TENORM are generated in the form of by-products, residues and wastes, from industrial processes that exploit natural resources such as coal combustion, fertilizers production, processing of metal, oil mineral ores extraction and, generally, many other industrial processing [1, 2, 3]. The management of these materials is receiving more attention compared to the past due to large volumes of generated NORM, low specific activities and very long lived radionuclides. NORM and TENORM should be evaluated as a pressing environmental hazard and should be monitored and treated with new specific techniques. This kind of contamination is dangerous when the
presence of unwanted substance is at concentration significantly above the ambient radioactive background, in this case, it can result in adverse biological effects to resident communities [4]. Gamma imaging is a technique based on the position and shape detection of gamma-ray radioactive sources. Inorganic scintillators equipped with photon detectors (e.g. PMTs or SiPMs) are among the most common devices for gamma-rays detection. Using 16 crystals coupled to 16 photomultiplier tubes we built a prototype based on coded mask technique and we tested it with radioactive sources, a nuclear waste drum and NORM samples. The main goal of this work is to measure spatial and energy resolution with different acquisition time and geometries. The final purpose of this work is to show the ability of the camera of localizing and identifying radioisotopes in the environment.

2. Coded mask technique
To explain the gamma camera working principle, we need to introduce, therefore, the concept of “camera obscura” or dark chamber. Imagine to cut a hole on one side of a closed box to allow light to enter the box with very strict geometrical constrains. This generates an inverted image of the light source on the opposite side of the box. The main drawback of this technique is the very low photon throughput. Indeed, to optimize the spatial resolution, a small hole is needed, which however results in a poor signal to noise ratio. The only way to improve the number of photons while keeping a good resolution is to make more than one hole [5]. A coded mask is a slab with opaque and transparent tiles (the holes) that allows the photons to project a shadow, or shadowgram, on a specific area (detecting area).

For our work a $7 \times 7$ mask was generated from a $4 \times 4$ MURA array (Modified Uniform Redundant Array) and was used to code the incoming gamma rays. Using a $4 \times 4$ array of scintillators, placed behind the mask on the opposite side of the radiation source, it is possible to distinguish 16 different shadowgrams at most (see figure 1). The distance between Camera and Mask defines the instrument, so called Full Coded Field Of View (FCFOV), which is the maximum viewing angle of the instrument in which the gamma-ray source can be fully coded. Taking advantage of geometry, we expect to keep the ratio between the distance of detector-mask and mask-source, equal to 3 to avoid ambiguity in source position reconstruction.

3. Experimental setup
The camera is composed by an array of $4 \times 4$ CsI(Tl) scintillators ($3 \times 3 \times 10 \text{ cm}^3$ each) coupled to photomultiplier tubes (PMT). The mask is located upstream the camera. It is built using a $4 \times 4$ MURA array. It has a throughput of 37.5%. The full $7 \times 7$ pattern was implemented by reproducing four times the main pattern and removing one line and one column [6]. The $7 \times 7$ mask is a slab composed by opaque tiles in tungsten and transparent tiles in PVC. The size of a single tile is $3 \times 3 \times 1 \text{ cm}^3$ and the size of the whole mask is $21 \times 21 \times 1 \text{ cm}^3$. PMTs (ET Enterprises, 9124B, 26% Quantum efficiency at peak) using a Cockcroft-Walton voltage multiplier as high voltage supplier (ET Enterprises, electron tubes, HV3020CN). Concerning the data acquisition, we used the digitizer CAEN V1725 to generate the trigger, digitize the signals and acquire the traces. The digitizer (V1725) is a $14 - \text{bit}$ device with a sampling frequency of 250 $\text{MS}/s$ on 16 channels. It is characterized by small dimension, low power requirements and it can be programmable with a PC. These features are very useful for our camera in order to build a compact and portable object. The signals acquired were integrated in order to obtain a counts spectrum.

4. Monte Carlo simulation
In order to test the camera performances a Toy Monte Carlo simulation was implemented, as first, to obtain a theoretical evaluation of the method. This simulation implements only the geometrical condition of the system and the gamma-rays absorption by the opaque tiles. The
nuclear interactions are ignored to guarantee a flexible and fast code. The gamma-rays are generated by the source and a matrix of counts is incremented every time a gamma-ray hits one channel of the camera. The mask distances from the camera and from the source are 5 and 15 cm, respectively. When a gamma-ray crosses a transparent tile nothing happens, on the contrary when it crosses the opaque one it is absorbed and disappears. As second step was coded a full Monte Carlo simulation based on GEANT4 [7, 8, 9] to take into account the proper radiation-matter interactions and the stopping power of the materials. The main structure of the simulation was similar to the toy Monte Carlo one, and the results was elaborated with the same algorithm. Only the Monte Carlo simulation results will be shown and compared.

The reconstruction test consists of a simulation of radioactive sources in random positions (on a plane at 20 cm from the camera). For each position (a run) we simulated a sample of $10^6$ radio-decay events. Figure 2, on the left side, shows how the rates change with the position of the source with respect to the mask. The count maps created for each simulation run was compared with a database of count maps corresponding to known radioactive source positions, using a two dimensional generalization of the Kolmogorov-Smirnov test [10, 11].

The theoretical resolution of the camera was estimated performing $10^4$ runs including $10^6$ events generated by GEANT4 by the class `G4RadioactiveDecay` to simulate the proper gamma-ray energy. Each simulation run was done in a random position within a calibration area of $48 \times 48 \text{cm}^2$ at 20 cm from Camera in a FCFOV of $1.8 \pi \text{ sr}$. We compared all the count maps produced with a count maps database (acquired during calibration), obtaining a reconstructed position for each run. Figure 2, on the right side, shows the histogram of the distance between the real position of the source and the reconstructed one (in cm), for which it is possible to calculate its quantile also known as Point Spread Function (PSF). The PSF describes the response of an imaging system to a point source or point object.

**Figure 1.** Different shadowgrams was produced by the mask on the camera placing the source in 16 different locations.
5. Analysis
We tested three different configurations. In the first configuration we placed a radioactive source at distance of 15 cm from the mask, and at 20 cm from the camera, as well as for the Monte Carlo analysis (see section 4). We tested this configuration with 2 sources, $^{60}$Co and $^{137}$Cs, in 4 different positions. Figure 3 shows the PSF results with respect the acquisition time. It is clear how in less than 2 minutes (100 seconds) the PSF 68% reaches the Monte Carlo value of 10 msr for $^{60}$Co and 61 msr for $^{137}$Cs. Nevertheless we need to wait few minutes to have the same with PSF 95%. $^{137}$Cs shows a softer convergence than $^{60}$Co mainly due to the fact that at low energy (620 – 680 for $^{137}$Cs and 1150 – 1350 for $^{60}$Co) the mask tungsten tiles have a better gamma absorption, and the mask works better. The second configuration was done putting a drum, generally used for nuclear waste storage (58 cm diameter and 88 cm height), at 50 cm from the camera (45 cm from mask). Inside the drum we put 2 radioactive sources ($^{60}$Co and $^{137}$Cs) as shown in Figure 4 on left side. The Figure 4 on center shows how the Camera can immediately, after 5 seconds, see an integral count rate clearly over the background, and generate an alarm status. The Figure 4 on right side shows how it is possible to use the spectrum information to make an imaging of the two sources with the same PSF within same acquisition time already shown in the previous configuration. In the third configuration, as shown in Figure 5 on right side, a igneous rock sample radioactivity was measured for 1 hour in a lead housing to reconstruct the spectrum. The long acquisition time was necessary to identify the peak, nevertheless the integral count rate in the region of interest (100 – 3000 keV) is very quickly to measure, as shown in the previous configuration and an alarm can be rapidly launched and, after few minutes the source can be identified and localized. The Figure 5 on left side shows the main peaks of interest in NORM analysis such as $^{40}$K, and the radioactive decay chains of $^{138}$U and $^{232}$Th.

6. Conclusions
For this work we developed and tested a prototype instrument for gamma-ray detection and imaging. Its design makes it compact, portable, ideal for in-situ, real-time and on the go measurements. The prototype camera is based on the coded mask technique and it was tested
Figure 3. The plots show the PSF at 68% and 95% for 4 different sources positions ((2, 2) cm; (2, 10) cm; (14, 14) cm; (−14, −10) cm for $^{60}$Co on the right side; (2, 2) cm; (6, −2) cm; (14, 14) cm; (−10, −6) cm for $^{137}$Cs on the left side) with respect different acquisition time. The sources activity were of 37 kBq for $^{60}$Co and 9.25 kBq for $^{137}$Cs. The Continuous straight line shows the Monte Carlo PSF expected values.

Figure 4. The left side plot shows the drum geometry with respect the two tested sources (inside at 5 cm from the front side); the central plot shows the integral count rate in the range of 600 – 1800 keV for radioactive drum and for background with respect the acquisition time. The right side plot shows the possibility to make an imaging for more than one source using the spectrum information to have a spatial identification.

using different radioactive sources and configurations. A full Monte Carlo model was developed for reconstructing the source position and for estimating the PSF. We presented three different configuration to show the ability to localize the single point sources with a PSF at 68% for $^{137}$Cs of 61 msr (1.5 cm at 20 cm from camera) and for $^{60}$Co of 10 msr (0.4 cm at 20 cm from camera) in less than 2 minutes. With the second configuration we also prove the possibility to identify an integral count rate over the background, in very few seconds, generating an alarm and, after few minutes, localize different sources using the spectrum data. Last configuration shows how to identify very quickly a NORM source and identify all the main peaks in about 1 hour in a lead housing. Future developments will involve the possibility to quantify the specific NORM
Figure 5. The right side picture shows the lead housing used for the acquisition of the NORM sample (an igneous rock) spectrum. Left side plot shows how the NORM activity is well distinguishable over the background. It is possible to find some radioactive peaks useful for NORM analysis, such as $^{40}K$, and the radioactive decay chains of $^{138}U$ and $^{232}Th$.

radionuclides using a proper calibration, replace the scintillator PMT with Silicon Photomultiplier to improve the energy resolution. An improvement of the geometry of the crystals and mask is foreseen to make the camera as compact and portable as possible, together with an optimization of the reconstruction algorithms for an improvement of the imaging resolution.

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