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Implementation of an Imaging Spectrometer for Localization and Identification of Radioactive Sources

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Abstract

Spatial localization of radioactive sources is currently a main issue interesting nuclear industry as well as homeland security applications and can be achieved using gamma cameras. For several years, CEA LIST has been designing a new system, called GAMPIX, with improved sensitivity, portability and ease of use. The main remaining limitation of this system is the lack of spectrometric information, preventing the identification of radioactive materials. This article describes the development of an imaging spectrometer based on the GAMPIX technology. Experimental tests have been carried out according to both spectrometric methods enabled by the pixelated Timepix chip used in the GAMPIX gamma camera. The first method is based on the size of the impacts produced by a gamma-ray energy deposition in the detection matrix. The second one uses the Time over Threshold (ToT) mode of the Timepix chip and deals with time spent by pulses generated by charge preamplifiers over a user-specified threshold. Both energy resolution and sensitivity studies demonstrated the superiority of the ToT approach which will consequently be further explored. Energy calibration, tests of different pixel sizes for the Timepix chip and use of the Medipix3 chip are future milestones to improve performances of the newly implemented imaging spectrometer.

Keywords

Gamma imaging; GAMPIX; Timepix; imaging spectrometer; Time over Threshold

1. Introduction

Spatial localization of radioactive sources is currently a main issue interesting nuclear industry (nuclear power plants security, decommissioning of nuclear facilities, radiation-protection) as well as homeland security applications (controls, post-accidental interventions)

42 [1] [2]. Gamma imaging is a very interesting technique to achieve this spatial localization by
43 enabling superimposition of visible and gamma pictures using dedicated devices called
44 gamma cameras.

45 Spatial localization can be achieved using Compton scattering or coded masks. Compton
46 approach includes two steps: the scattering of the incident photon and its full absorption.
47 From the path of each incident photons one can determine cones from which it could have
48 been emitted. The radioactive source is located at the intersection of all the rebuilt cones. Two
49 sensors are usually involved in these systems but gamma cameras based on a single sensor
50 also exist. We can give the example of the recently industrialized Polaris-H system [3] [4]. In
51 this new gamma camera, the depth of interaction required to determine the path is obtained
52 from the cathode-to-anode signal ratio (CAR) or from drift time information. Because photons
53 have to deposit energy in two successive detectors, the Compton approach is mainly dedicated
54 to photons above 200 keV [3]. In the rest of the article, we will focus on gamma cameras
55 using coded masks.

56 Current industrial gamma cameras based on coded masks can be considered as first generation
57 because they are based on scintillator detectors. Much progress was made since the design of
58 the first gamma camera by Hal Anger (Berkeley University, California) in the last's 50 for
59 medical applications [5]: digitalization of data processing [6], replacement of the pinholes
60 used for spatial localization (CARTOGAM, CEA LIST [7]) by multiple hole collimators
61 (Fixed Multiple hole Collimated Camera, University of Michigan [8]) and MURA coded
62 masks (RadCam, Radiation Monitoring Devices Inc. [9]), etc. In the 90's, continuous
63 scintillators moved into pixelated scintillators (CSPD-2, University of Michigan [10]; RMD-
64 Pinhole, Radiation Monitoring Devices Inc. [11]). At the same time, semiconductor detectors
65 were developed [6]. Such detectors intended to improve both spatial and energy resolution by
66 enabling direct conversion from gamma photons to electrical charge. First gamma cameras
67 integrating semiconductor detectors present some limitations because of small detection
68 surfaces resulting in small fields of view ([12, 13]) and obligation of cooling the detector
69 when using materials such as germanium [12]. The progressive development of pixelated
70 CdTe or CdZnTe substrates hybridized to ASICs [14, 15, 16, 17] opened the way to a second
71 generation of gamma cameras operating at room temperature.

72 In this context, CEA LIST designed a second generation system, named GAMPIX [1, 18, 19].
73 GAMPIX's body integrates three main building blocks:

74 The detection system is a 1 mm thick CdTe substrate bump-bonded to a pixelated readout
75 chip called Timepix [17] and developed by the CERN. In 1.4 cm², the Timepix chip integrates
76 256 pixels by 256 pixels, 55 μm side, with independent shaping and processing chains.

77 In front of the detection system, the coded mask in tungsten alloy is used as a multi pinhole
78 collimator for spatial localization [20]. It is characterized by its number of holes (rank) and its
79 thickness.

80 Finally, the USB module enables plug-and-play connection of the gamma camera with the
81 acquisition laptop [21] and remote measurements.

82 GAMPIX is currently under industrialization by AREVA CANBERRA (the industrial system
83 is named iPix, see Fig. 1). Compared to CARTOGAM, which is the current AREVA
84 CANBERRA industrial system, GAMPIX presents three main improvements:

85 The first one is the low-energy (below 100 keV) sensitivity with a gain of five decades in
86 comparison with CARTOGAM. GAMPIX is able to detect in 1 s a ^{241}Am radioactive source
87 generating a dose rate of $0.25 \mu\text{Sv}\cdot\text{h}^{-1}$ in the vicinity of the gamma camera. For this reason,
88 GAMPIX is a performing tool for plutonium detection during decommissioning operations
89 (^{241}Am being a feature of the presence of plutonium). GAMPIX efficiency decreases at high
90 energy because of both the small detection volume (0.1982 cm^3 of CdTe against 5 cm^3 of
91 CsI(Tl) for CARTOGAM) and the non-perfect filtering achieved by the coded mask. For this
92 reason, 20 s are needed to detect a ^{137}Cs radioactive source with $2.5 \mu\text{Sv}\cdot\text{h}^{-1}$ dose rate and 60 s
93 for a ^{60}Co source giving a dose rate of $3.8 \mu\text{Sv}\cdot\text{h}^{-1}$. However, it is important to emphasize that,
94 by adapting the characteristics of the coded mask, GAMPIX is able to cover an energy range
95 from ^{241}Am to ^{60}Co with better performances than CARTOGAM even at high energy (see [1]
96 for results obtained in Nuclear Power Plants).

97 The second point is the portability facilitated by the reduction of the weight. CARTOGAM,
98 which is the lightest system currently on the market, and GAMPIX respectively weight 15 kg
99 and 2 kg. The difference is mainly due to the shielding required by the scintillation detector of
100 CARTOGAM.

101 Finally, the third point deals with the ease of use and deployment of GAMPIX in comparison
102 with CARTOGAM. GAMPIX uses for instance only one cable for camera management, data
103 transmission and power supply.

104 Besides, GAMPIX has a field of view of 50° . The angular resolution, which refers to the
105 minimal angle between two radioactive sources to be separated in the decoded image, reaches
106 down to 2° for a ^{241}Am radioactive source.

107 GAMPIX applications benefit from its characteristics. Thanks to its great portability, it can
108 easily be deployed in nuclear power plants in order to control, for instance, the correct
109 position of lead shielding dedicated to the radiation protection of operators. Regarding nuclear
110 facilities decommissioning, GAMPIX is able to provide an accurate localization of hot spots
111 (for instance, in pipes) for targeted decommissioning enabling both reduction of operations
112 duration and waste volume to be stored. The sensitivity of GAMPIX and its easy deployment
113 by non-expert end-users enable its use for fast control of luggage (airports) and containers
114 (ports) for homeland security applications. Finally, for post-accidental interventions,
115 GAMPIX can help the first responders to quickly identify dangerous areas in Fukushima type
116 environments. Experimental results illustrating these applications can be found in the
117 Reference [1].

118 In its current version, the main limitation of the GAMPIX gamma camera is the lack of
119 spectrometric information, preventing the identification of radioactive material. Thus, dose
120 rate calculation needs an assumption on the nature of radionuclides and it is impossible to
121 identify different radionuclides simultaneously present in the environment. Considering this
122 limitation, it was decided to add new spectrometric capabilities to the GAMPIX gamma
123 camera to achieve an imaging spectrometer.

124 The Timepix chip offers two approaches for performing spectrometry measurements. The first
125 one is based on the average size of the clusters which directly depends on the energy of the
126 incident gamma-ray. As an example, the average cluster size is contained for a given Timepix
127 energy threshold between 2.8 pixels for a ^{241}Am source and 7.0 pixels for a ^{60}Co source. The
128 incident average energy can thus be deduced from the average cluster size. The second
129 approach uses the Timepix Time over Threshold (ToT) mode [17, 22, 23]. By setting a
130 threshold on pulses obtained at the output of charge sensitive preamplifiers, ToT mode
131 measures the time spent by the pulses over the threshold, which is directly dependent on the
132 incident gamma-ray energy. Conversion between cluster sizes or ToT values and energy can
133 be achieved using reference radioactive sources or monoenergetic beams.

134 The purpose of this article is to demonstrate the ability of the GAMPIX system to provide
135 spectrometric information. Qualitative and quantitative evaluation of its performances
136 regarding this purpose will be presented. The first part of the document is dedicated to the
137 preliminary setting of the Timepix chip and to the description of the required analysis tools. In
138 the second part, methodology for implementing the imaging spectrometer and evaluation
139 criteria of the final system are presented. Finally, the last part summarizes experimental
140 results obtained in the frame of this study.

141 **2. Settings of the Timepix chip and analysis tools**

142 Fine tuning of the Timepix chip settings was crucial prior the implementation of the imaging
143 spectrometer. It aims at optimizing both energy resolution and gain. Settings and data
144 acquisition were performed using the Pixelman interface developed in the Czech Technical
145 University of Prague [24]. First, threshold equalization with “noise edge” method was carried
146 out to minimize dispersion around the average threshold value caused by gain differences
147 between pixels. Then, a parametric study on the thirteen chip parameters showed that the I_{krum}
148 DAC had the greatest influence on both energy gain and energy resolution [25]. The I_{krum}
149 current both controls falling times of pulses generated by charge preamplifiers and
150 compensates leakage currents (within the limit of $I_{krum}/2$). All parameters were finally set to
151 their default value, except I_{krum} which was set to the DAC code value 2 corresponding to a
152 falling time in the order of $1\ \mu\text{s}$ [26]. It is important to notice that the pile-up is limited with
153 such a value. The substrate bias voltage has to be high enough (in absolute value) to minimize
154 charge spreading and charge trapping which is a drawback of CdTe. In our case, bias voltage
155 was set to $-110\ \text{V}$. Conversion between ToT values and energy can be done by mean of a
156 calibration curve [27-28]. This curve is mostly linear, except at very low energy (just above
157 the threshold set on the pulses). Energy calibration also aims at optimizing energy resolution
158 by correcting the shift between peaks due to clusters of different sizes (Fig. 2). In this study,
159 we tested our imaging spectrometer without energy calibration but directly with ToT values.
160 It is important to emphasize on the fact that energy resolution improvement given by the
161 energy calibration step was not crucial for these measurements because gamma-ray spectra
162 coming from the different studied radionuclides have a typical signature (Table I).

163 Data processing was performed with dedicated MATLAB software developed by CEA LIST.
164 This software implements processing functions dealing with both spectrometric approaches

165 tested in the imaging spectrometer. Concerning cluster size, the software identifies clusters as
166 set of neighboring pixels. A maximal allowed cluster size can be set by the user to remove
167 cosmic rays, size of which commonly exceeds 20 pixels. It is important to set a low enough
168 acquisition time per frame to avoid pile-up which would lead to non-physical clusters
169 resulting from the sum of successive close events. Cluster size histograms giving the number
170 of occurrences depending on the cluster size are finally plotted. As far as ToT mode is
171 concerned, the software sums ToT values of all pixels forming a cluster. If energy calibration
172 has been achieved, energy conversion is done before summation. Spectra giving the number
173 of occurrences as a function of ToT values are finally plotted. The software also achieves
174 spatial reconstruction from the coded mask projection on the detection matrix. Spatial
175 reconstruction can be focused on a given cluster size windowing or ToT windowing specified
176 by the user. This functionality will be used for the implementation of the imaging
177 spectrometer as presented in section III.

178 **3. Implementation of the imaging spectrometer and evaluation criteria**

179 To demonstrate the feasibility of an imaging spectrometer based of the GAMPIX gamma
180 camera, it was decided to develop a device achieving a selective spatial reconstruction
181 depending on the energy of incident photon (via cluster size and ToT values). This device was
182 tested with four radioactive sources covering the energy range of interest for the GAMPIX
183 system (see Table I). Performances of both spectrometric approaches in terms of
184 discrimination capability, and comparison with the GAMPIX gamma camera in its current
185 version in terms of sensitivity were assessed. The first part of this section is dedicated to the
186 methodology used for the implementation of the imaging spectrometer while the second part
187 justifies the choice of evaluation criteria.

188 **3.1 Implementation of the imaging spectrometer**

189 Implementation of the imaging spectrometer according to both cluster size and ToT values
190 approaches is based on windowing. Cluster size windowing requires a preliminary
191 measurement with each radionuclide taken alone. From the cluster size histograms, mean
192 cluster size, dispersion around the mean and overlapping between radionuclides are evaluated.
193 The first spatial reconstruction is performed on the single mean cluster size. Then, the
194 windowing is progressively broadened and the best configuration is determined by
195 qualitatively evaluated spatial reconstructions. To appreciate differences between cluster size
196 histograms, Fig. 3 shows histograms of ^{241}Am and ^{60}Co radioactive sources and Table II gives
197 mean cluster size and percentage of clusters in different ranges for the four radionuclides
198 tested. Table III summarizes the cluster size windowing chosen for best discrimination. To
199 avoid overlapping between radionuclides, mean cluster size and most frequent cluster sizes
200 are not necessarily included in the windowing.

201 Concerning ToT windowing, a preliminary measurement with each radionuclide taken alone
202 is also required to identify in the spectra ToT values associated with typical features
203 (photoelectric peaks, Compton edge, etc.) Spectra obtained with each radionuclide are then
204 compared to determine if there is overlapping due to the energy resolution of the sensor. The

205 first windowing is centered on typical features and the best windowing is finally obtained by
206 sequential approach. Typical features of the four radionuclides studies and position of the
207 windowing are shown in Fig. 4. All ToT spectra obtained are in good agreement with
208 previous literature results [27] and show the ability of the ToT mode to provide useful
209 gamma-ray spectra, even at high energy (^{137}Cs and ^{60}Co). One can notice the large fraction of
210 events on the fluorescence and escape peaks. It is explained by the pixelation of the detector:
211 it is unusual that both incident photon and fluorescence photon deposit their energy in the
212 same 55- μm -side pixel. Table IV summarizes ToT windowing for all tested radionuclides.
213 Because of overlapping, windowing does not necessarily include typical features.

214 **3.2 Evaluation criteria**

215 The first evaluation criterion of imaging spectrometer performances is the discrimination
216 ability, which is qualitatively evaluated from spatial reconstructions. If radionuclides with
217 different gamma-ray emissions are simultaneously present in the field of view, the
218 discrimination ability characterizes the ability of the system to reconstruct only radioactive
219 sources included in a given energy range.

220 The second evaluation criterion is the sensitivity, which corresponds to the minimal duration
221 required for detecting a radionuclide inducing a given dose rate near the gamma camera. The
222 sensitivity corresponds to a picture free of artifacts, as shown in Fig. 5 (b). Three parameters
223 have a great impact on the sensitivity. The first one is the detector efficiency. It decreases
224 when the incident gamma-ray energy increases as shown in Fig. 6. For a 1-mm-thick CdTe
225 detector, efficiency drastically decreases from 100 keV. The second factor is the coded mask
226 and its characteristics. A tradeoff has to be found between thickness (sensitivity) and number
227 of holes (i.e. the rank, which defines the angular resolution). The last factor is the energy
228 windowing. Without windowing (standard working mode for the GAMPIX gamma camera),
229 all photons hitting the detector are taken into account. The narrower windowing is, the fewer
230 photons are considered, and the more sensitivity is decreased.

231 **4. Performances of the imaging spectrometer**

232 Performances according to both evaluation criteria presented in section III are successively
233 presented. All acquisitions were performed in “Time over Threshold” mode and in “frame”
234 type with 1 s acquisition per frame. They were repeated three times to control reproducibility.

235 **4.1 Discrimination ability**

236 To evaluate discrimination capability, radioactive sources were disposed two or three at a
237 time in front of the gamma camera over a graduated table. Tests were carried out for distance
238 between radioactive sources and GAMPIX gamma camera varying between 50 cm and
239 150 cm on the camera axis and between 0 and 50 cm on each side of the camera on the
240 perpendicular axis. Acquisition time was set between 300 s and 2000 s depending on
241 configurations tested.

242 Table V shows pictures obtained after both cluster size windowing and ToT windowing for a
243 1500 s acquisition with ^{241}Am , ^{133}Ba and ^{137}Cs radioactive sources positioned in the
244 configuration illustrated in Fig. 7. Both approaches are efficient for ^{241}Am and ^{137}Cs
245 discrimination but cluster size windowing is unable to separate ^{133}Ba from ^{241}Am . ^{137}Cs also
246 appears less punctual for cluster size configuration and there are more artifacts on ^{241}Am
247 picture. All tested configurations proved the superiority of ToT approach on cluster size
248 approach regarding this evaluation criterion.

249 Three factors explain this superiority. First, spectra of the four radionuclides tested are well
250 differentiated contrary to cluster size plots: centroid of photoelectric peaks varies from about
251 500 to 4500 from ^{241}Am to ^{60}Co (Fig. 4), while mean cluster size only changes from about 3
252 to 7 (Table III). Secondly, the 11810 channels of the counting system in ToT mode are great
253 enough to show these differences. Finally, ToT mode enables to carry out fine spectrometry
254 measurements while cluster size mode only deals with mean energy values.

255 **4.2 Sensitivity**

256 During our experiments, sensitivity was determined for each source placed at 1 m from the
257 gamma camera in the camera axis, without windowing, with cluster size windowing and with
258 ToT windowing. Several configurations of the mask were tested. We were looking for the loss
259 of sensitivity induced by the spectro-imaging mode for both spectrometric approaches with
260 respect to the GAMPIX gamma camera in its current version.

261 Tables VI to VIII summarize sensitivity for all radionuclides tested without windowing
262 (GAMPIX gamma camera in its current version) and with cluster size and ToT windowing for
263 several configurations of the coded mask. Percentages below the values indicate the loss of
264 sensitivity due to both windowing techniques.

265 Several conclusions can be drawn from these results. Concerning coded masks, the one of
266 rank 7 with a thickness of 4 mm produces best results for energies under 100 keV (^{241}Am ,
267 ^{133}Ba), while mask of rank 7 with a thickness of 8 mm is more efficient for higher energies
268 (^{137}Cs , ^{60}Co). Rank 13 offers better performances than rank 7 in terms of spatial resolution but
269 is less efficient in terms of sensitivity. Two millimeters appears to be a too-thin thickness for
270 each of the tested radionuclides, especially for high-energy gamma-ray emissions. In the case
271 of unknown searched radionuclides, coded mask of rank 7 with a thickness of 4 mm offers the
272 best tradeoff.

273 Concerning energy windowing, it causes a loss of sensitivity greater than 20% in most cases,
274 which is explained by the little fraction of events occurring in the sensor and finally selected
275 for spatial reconstruction. For low energies, this sensitivity loss is not a real problem because
276 of very small acquisition times required by the GAMPIX gamma camera (from 1 s to 2 s for
277 ^{241}Am with rank 7 and thickness of 8 mm for the coded mask). For higher energies, loss can
278 be limited by the choice of the most adapted mask. Best sensitivities are obtained for ToT
279 windowing in comparison with cluster size windowing. Degraded results with ^{60}Co are
280 explained by photoelectric peak spreading due to the high mean cluster size (7) and to the
281 dispersion around this value which causes shifts between photoelectric peaks.

282

5. Conclusion and outlook

283 The purpose of our study was to demonstrate the feasibility of an imaging spectrometer based
284 on the GAMPIX gamma camera and to evaluate its performances. Two methods were tested
285 to implement this imaging spectrometer: cluster size and ToT approaches. Tests on
286 discrimination ability and sensitivity both proved the feasibility of such a device and the
287 superiority of ToT approach. Loss of sensitivity with ToT approach is greater than 20%. If it
288 is not a problem for low energies, a relevant choice of the mask can mitigate this drawback
289 for energies higher than 100 keV. If the radionuclide is unknown, the coded mask of rank 7
290 with a thickness of 4 mm offers the best compromise.

291 Further developments of the imaging spectrometer will combine both cluster size and ToT
292 spectrometric approaches. Next planned step is the integration of the energy calibration in the
293 imaging spectrometer for the analysis of closer gamma-ray energies. Because of the high
294 mean cluster size, improvements are also expected for high energies (^{60}Co). Energy
295 calibration measurements should take place at the SOLEX facility which provides
296 monoenergetic beams from 0.5 keV to 28 keV [30]. As a first step, we plan the global
297 calibration of the Timepix chip. Improvements of the energy resolution of a factor between
298 two and four are reported by [26] with a pixel by pixel calibration and this approach will be
299 considered as a second step. Test of a 1 mm thick, 110 μm pixel side Timepix chip is also
300 expected. It would enable to evaluate the energy resolution gain due to the limitation of
301 charge sharing between several pixels, which is one of the main explanations for energy
302 resolution degradation.

303 Finally, the replacement of the Timepix chip by a Medipix3 chip will be studied. The ToT
304 mode is not implemented in the Medipix3 chip and spectra have to be obtained by counting
305 the number of events for each threshold value [31]. The main improvement compared to
306 previous Medipix chips concerns the hardware connection between several neighboring
307 pixels, which should drastically improve the energy resolution of the system.

308

309 References

310

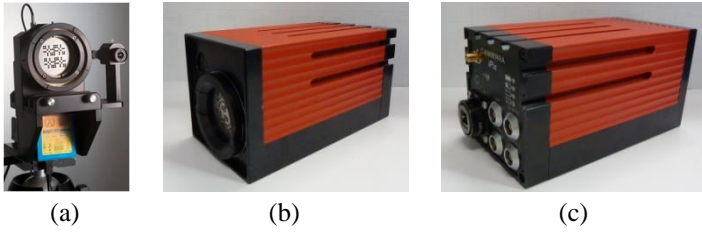
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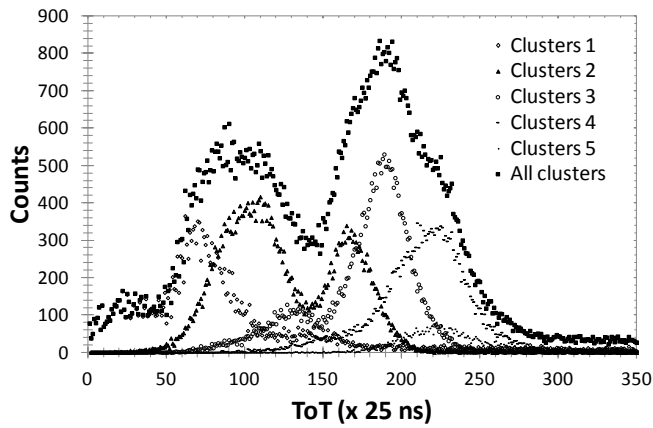
379 **Figures**

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381 Fig. 1: (a) GAMPIX gamma camera prototype developed by CEA LIST (b) front side and (c) back side of the
382 iPix industrial prototype developed by CANBERRA.

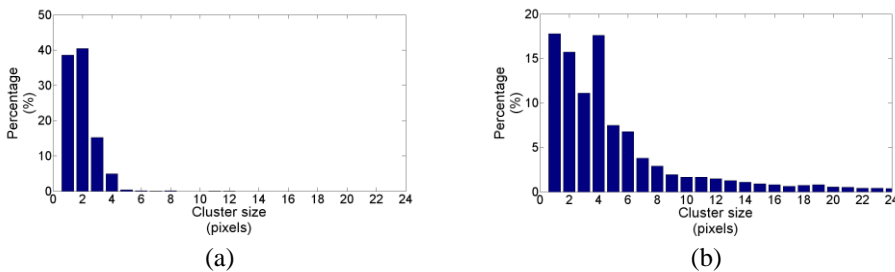
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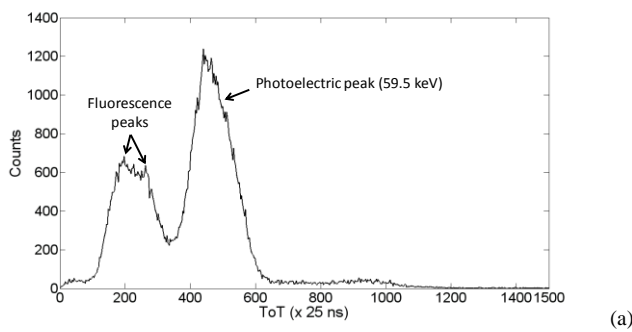
385 Fig. 2: Spectra obtained with a ^{241}Am radioactive source depending on cluster size.

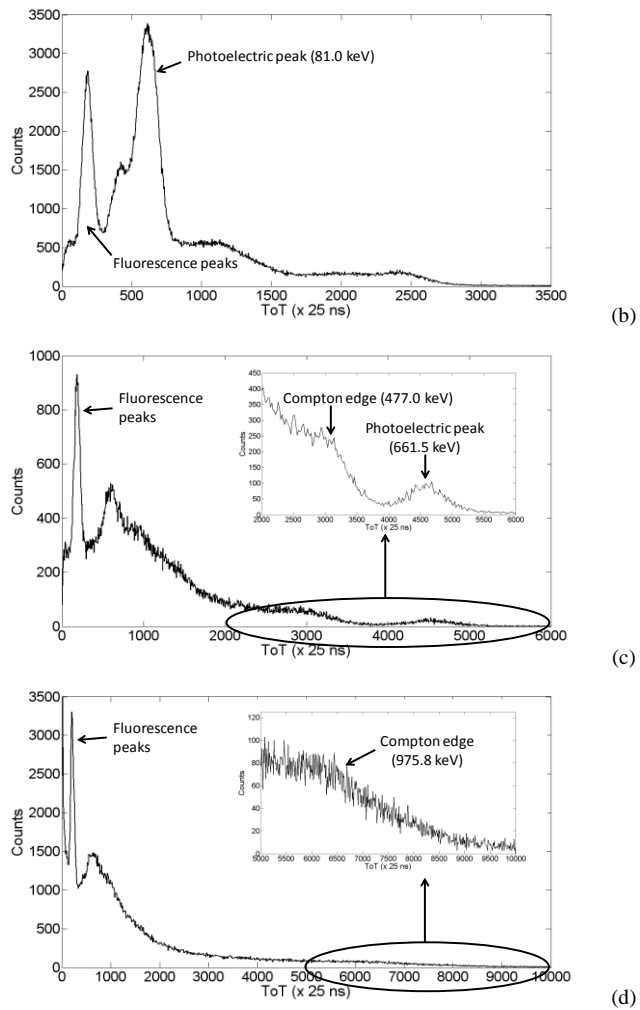
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387 Fig. 3: Cluster size histograms for (a) ^{241}Am and (b) ^{60}Co

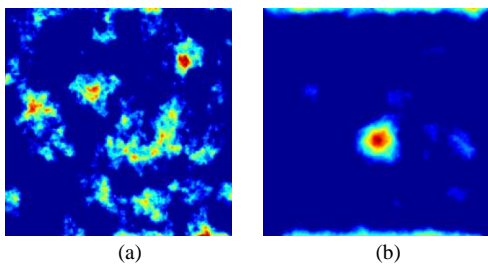
388





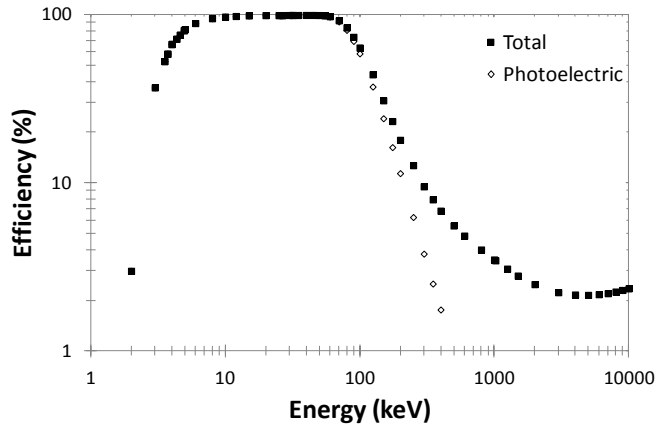
389 Fig. 4: Spectra of (a) ^{241}Am , (b) ^{133}Ba , (c) ^{137}Cs and (d) ^{60}Co with typical features.

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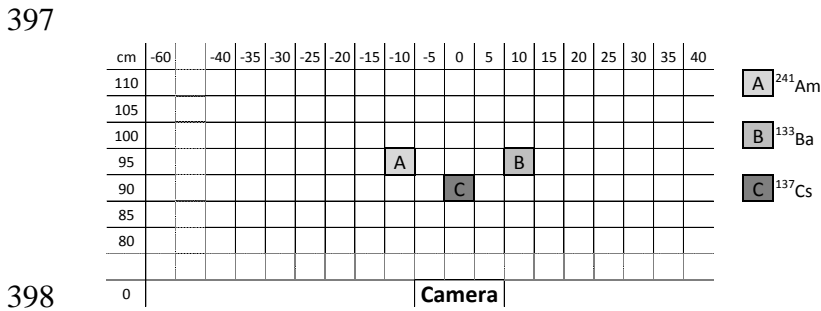


391 Fig. 5: Spatial reconstruction of a radioactive source of ^{137}Cs (coded mask of rank 7 with thickness of 4 mm) for
 392 acquisition time of (a) 10 s and (b) 400 s. The presence of artifacts can be observed on the left. Result obtained
 393 for a 400 s acquisition time is considered as satisfying.

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396 Fig. 6: Logarithmic plot of efficiency for 1 mm CdTe detector between 1 keV and 10 MeV.



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399 Fig. 7: Example of the experimental configuration used to evaluate both spectrometric approaches. Workbench
400 on which radioactive sources are placed is seen from above.

401
402 Tables

403
404
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Table 1
Characteristics of radioactive sources tested

Source	²⁴¹ Am	¹³³ Ba	¹³⁷ Cs	⁶⁰ Co
Energy (keV)	59.5	[81.0, 356.0]	661.7	1173.2 and 1332.5
Activity (MBq)	72.8	35.1	26.1	11.7
Dose rate at 1 m (μSv/h)	0.286	1.658	1.987	3.585

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Table 2
Mean cluster size and cluster size probabilities

Radionuclide	Mean cluster size (pixels)	Cluster size probability (%)		
		0-4	4-10	> 10
²⁴¹ Am	2.8	90.1	9.8	0.1
¹³³ Ba	3.9	70.4	28.4	1.2
¹³⁷ Cs	4.4	59.9	35.4	4.7
⁶⁰ Co	7.0	54.6	30.8	14.6

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Table 3
Cluster size windowing

Radionuclide	Windowing (cluster size)	Mean cluster size (pixels)
²⁴¹ Am	0-3	2.8
¹³³ Ba	7-10	3.9
¹³⁷ Cs	10-100	4.4
⁶⁰ Co	12-100	7.0

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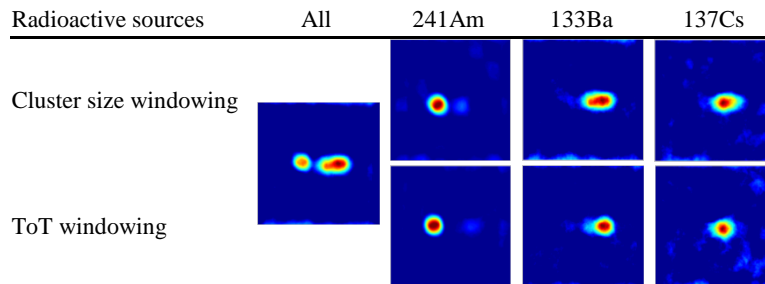
413
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Table 4
ToT windowing

Radionuclide	Windowing (ToT values)
²⁴¹ Am	400-500
¹³³ Ba	600-800
¹³⁷ Cs	1000-2000
⁶⁰ Co	5000-15000

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Table 5
Mean cluster size and cluster windowing



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Table 6
Sensitivities without windowing and for cluster size and ToT windowing with rank 7, thickness of 4 mm coded mask

	Without windowing	Cluster size windowing	ToT windowing
²⁴¹ Am	1 s	1 s 0%	1 s 0%
¹³³ Ba	4 s	15 s +275%	7 s +75%
¹³⁷ Cs	60 s	130 s +117%	100 s +67%
⁶⁰ Co	300 s	400 s +33%	1500 s +400%

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Table 7
Sensitivities without windowing and for cluster size and ToT windowing with rank 7, thickness of 8 mm coded mask

	Without windowing	Cluster size windowing	ToT windowing
²⁴¹ Am	1 s	2 s +100%	2 s +100%
¹³³ Ba	10 s	25 s +150%	12 s +20%
¹³⁷ Cs	20 s	180 s +800%	80 s +300%
⁶⁰ Co	60 s	125 s +108%	650 s +983%

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Table 8
Sensitivities without windowing and for cluster size and ToT windowing with rank 13, thickness of 2 mm coded mask

	Without windowing	Cluster size windowing	ToT windowing
²⁴¹ Am	3 s	4 s +33%	4 s +33%
¹³³ Ba	14 s	100 s +614%	17 s +21%
¹³⁷ Cs	300 s	> 600 s > +100%	> 600 s > +100%
⁶⁰ Co	Not visible	Not visible	Not visible

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