Modeling of gamma-ray spectrometers in MATLAB for analysis and optimization in acquisition, processing and interpretation of radiometric data.

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Abstract

One of the major concerns in the nuclear techniques is the precision in obtaining the radiation counts for elements in rocks and ground. The large amount of experimental uncertainties in detection of gamma-ray makes optimization of techniques a difficult task. Using a mathematical model, it is possible to avoid several of these difficulties.

In this paper the implementation of a gamma-ray spectrometry model will be presented. It covers the radiation source, the gamma-ray crystal detector, the detector of pulses, the counting process and the storage of spectral energies.

Modeling the rate of radiation emitted for each element, we can optimize the efficiency and resolution of the sensor through variations in the parameters of the model and algorithms of data processing faster and with fewer costs in the experiments.

Introduction

In nuclear measurements, the main objective is the determination of the energy of the pulses proceeding from a detector with the best possible resolution.

To determine these pulses, a good pulse detector and processor are necessary with minimum inherent factors such as electronic noise, piling up and others.

To optimize the processor and pulse detector system, we decided to use MATLAB to model the crystal detector systems found on the market. It made easier and more flexible the design of a radiation processor and pulse detector system. This model can simulate different designs with no need to assemble the different electronic circuits to perform the tests.

Traditionally, the processor and pulse detector are analog circuits, which have inherent non-linearities and vary considerably with time and temperature. Digital pulse detectors and processors will be developed and simulated with this model and their performance will be analyzed.

We can use the model to answer some questions such as how the characteristics of crystal detectors influence performance and resolution. The model can be changed and implemented with the complexity and detail needed to match the questions in mind.

Method

The gamma-ray spectrometer model was developed in MATLAB/SIMULINK and is composed of five basic blocks (see figure 1).

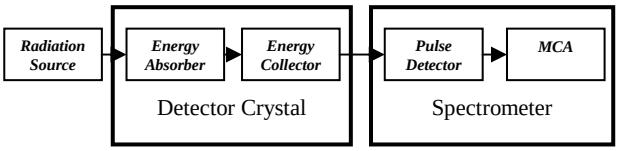

Figure 1 – Block Diagram of gamma-ray spectrometer model.

Each block is described below:

Radiation Source: In this block, we can configure the decay rate of gamma-ray that interacts with the sensor in a specific period for each desired element. Using elements that are used as sample for equipment calibration or elements normally found in the rocks and ground we can model the most common situations in gamma-ray spectrometry and compare results between the model and real sensors. The precise moment that a photon interacts with the crystal is determined by the distribution of Poisson. Elements as Uranium and Thorium produce all daughters in simulation.

Energy Absorber: In this block, is defined the kind of interaction of the gamma-ray with the matter and the length of absorption through the linear attenuation coefficient of the matter. The linear attenuation coefficient depends upon the energy of the radiation and it is possible to determine the probability of which kind of interaction can happen. Photoelectric absorption interactions are dominant in low energies and absorb completely the gamma-ray energy. Pair production is dominant in high energy and produces two other gamma-rays with 511 KeV each. Compton scattering is most important in the mid-energy level range and the energy is partially absorbed depending upon collision angle of the gamma-ray.

In every interaction the absorbed energy is determined and the new energy, position and direction of the resulting gamma-ray photons in the crystal are calculated. Wall reflection and escapes are also correctly accounted for in the model. The length of absorption path and the collision angle in Compton scattering dependence on energy values and probabilistic distributions are also calculated.

Energy Collector: In this block where uncertainties in the reading of the energy captured in the energy absorber are determined.

In Scintillation crystals, the conversion efficiency of the absorbed energy is around 12%. In addition, about 170 eV are needed to produce a photoelectron. Furthermore, the collection efficiency of these photons by the photomultiplier is around 20% with an additional uncertainly variance. All these uncertainties have been modeled.

In semiconductor crystals, the uncertainties are much smaller than in scintillation crystals. Two have been modeled. The first is the fluctuation of the number of electron-hole pairs created (2.96 eV are necessary to create each one). The second is the incomplete load collection. The time of absorption of a photon is much smaller for a semiconductor detector than for a scintillation one. There is no photomultiplier in semiconductor detector. The production of large numbers of information carriers is the main reason for the superior performance of semiconductors in general.

Uncertainties affecting both types of detectors have also been modeled. Electronic noise causes variations in pulse detection. It is possible insert noise signal in photomultiplier and pre-amplifier.

Pulse Detector: This block detects and measures the amplitude of individual pulses output from the pre-amplifier. This amplitude is proportional to the energy of the gamma-ray absorption within the detector. Both analog and digital pulse detectors have been modeled. In the conventional analog circuit, individual pulses are reshaped with a longer time for easier detection of their amplitude. In the digital circuit, the output signal of the pre-amplifier is directly sampled. Digital signal processing algorithms detect the peaks of individual pulses.

MCA: The multichannel analyzer collects, counts and stores the energy of each gamma-ray during a pre-determined period. It processes, corrects and displays the data in a spectral energy histogram with a configurable number of channels. The windows used for obtaining the counts of elements can be easily configured.

Simulation examples

Two series of simulations have been carried out to evaluate the functionality of the model. In the first series, spectra were obtained for varying detector types and sizes. In the second series, the performance of the pulse detector was evaluated.

At first, we obtained spectra for the element ^{60}Co. We validated it with samples collected in real detectors of germanium and sodium iodide. Cobalt is usually used for the calibration of detectors. In Beta decay mode it produces two energies, 1173 and 1332 KeV with 0.9986 and 0.9998 emission probabilities respectively (Gilmore, 1995, p.295).

We can see the results of the simulation in figure 2. On the left, we have the results for ^{60}Co with a NaI(Tl) detector and on the right, the results with a Germanium detector. Both detectors have the same dimensions (3''X3'') and 512 channels were used in the MCA.

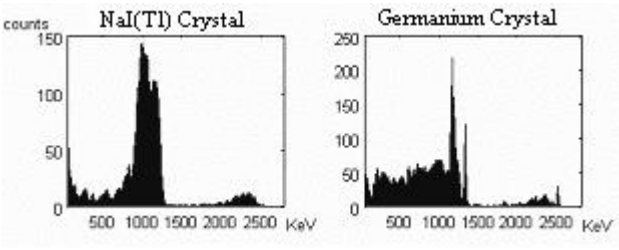

Figure 2 – Energy spectrum for ^{60}Co in NaI(Tl) (left) and germanium (right) detector of size 3''X3'' simulation

In figure 3 we can see the results for Potassium, Uranium and Thorium, using a much smaller detector with dimensions 0.1''X0.1''. in this simulation, only the main peaks were modeled: 1460 KeV for potassium (^{40}K), 1764 KeV for Uranium (^{214}Bi) and 2614 KeV for Thorium (^{208}Tl). In this very small detector, it is very unlikely that more than one interaction would happen for a Gamma-ray photon. We can see that pair production is seen only in higher energies (greater than 1500 KeV).

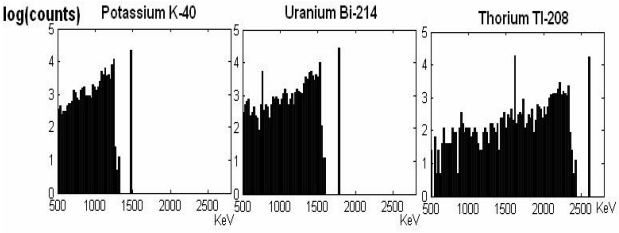

Figure 3 – Energy spectrum for ^{40}K (left),^{214}Bi(center) and ^{208}Tl (right) in germanium detector of size 0.1''X0.1'' simulation

In figure 4 we see the results for a very large detector 1000''x1000''. With this size of detector, it is very unlikely that a photon would escape it without total absorption. Note the difference between the resolutions for scintillation and semiconductor detectors. This is despite both having similar efficiencies and identical dimensions. The difference is explained by the larger detection uncertainty in the scintillation detector.

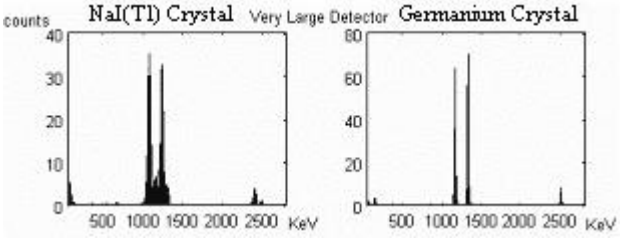

Figure 4 – Energy spectrum for ^{60}Co in NaI(Tl) (left) and germanium (right) detector of size 1000''X1000'' simulation

Results for a digital peak detector

With the converters available today, we can acquire signals with great precision and speed (more than 100 million samples per second). This makes it possible to replace the analog pulse amplifier with a digital signal

processor, avoiding disadvantages to the analogical circuits such as time and temperature changes. It also opens up new possibilities, such as the use of optimized filters. Figure 5 shows a block diagram of a digital spectrometer.

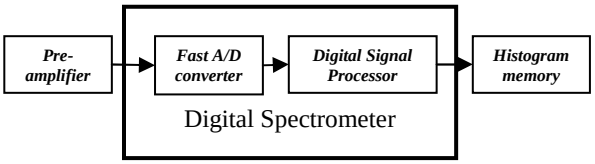

Figure 5 – Block Diagram of digital spectrometry.

Simulating the pre-amplifier output response of a scintillation NaI(Tl) detector, we can experiment with different designs of digital peak detectors.

The model makes performance analysis possible without the need for acquiring expensive A/D converters or assembling complex electronics circuits.

One major difficulty in pulse detection is the time resolution available to detect the exact moment it occurred, which affects the precision of the measurement of pulse amplitude. Figure 6 shows the discrete signal of the detector output signal and how it is possible to loose amplitude information depending on sample time of the D/A converter used.

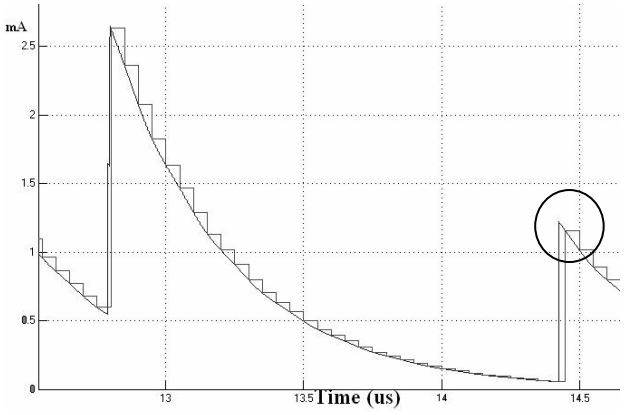

Figure 6 – Discrete signal of detector output signal at 20 MSPS.

Table 1 shows the results of performance for different sample rates of A/D converters. Peak amplitudes were detected using simple backward difference. The theoretical FWHM of NaI(Tl) for the energy of 1332 KeV (^{60}Co) is 35,4 KeV (Gilmore, 1995, p.218).

Table 1 – Resolution FWHM analysis for ^{60}Co at energy of 1332 KeV for different sample rates of A/D converters.

Sample rate (MSPS)	FWHM (KeV)
20	108
50	52
100	36
2000	24

As the pulse decay rate is about 230 ns, we see that for a sample rate of 20 MSPS (one sample every 50 ns), the resolution is very poor. With at least 10 samples during the decay (230ns), the resolution becomes acceptable if with the implementation of a good algorithm, to minimize the measurement error of the peak amplitude.

Conclusions

We saw in this work how easy it is to work with a model. Parameters and configurations can be changed without the need of costly and time consuming modifications in circuits and components. This enables us to carry out studies with the aim to increase performance while optimizing the efficiency and precision of a detector.

The simulations demonstrate the ease with each the analysis of different designs can be executed.

We can use the model to answer questions about characteristics of detector crystals and how they influence performance. The harder the question the more complex the model can be. Currently, we can change some parameters and characteristics such as luminescence and phosphorescence decay times, dimension of walls and crystals, linear attenuation coefficient curves, energy necessary to produce a photoelectron, uncertainty of energy collector and others. In practice, it is impossible to modify such crystal and detector characteristics with the same flexibility and cost effectiveness.

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Acknowledgments

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