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Pile-up correction algorithm based on successive integration for high count rate medical imaging and radiation spectroscopy

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ABSTRACT

In high count rate radiation spectroscopy and imaging, detector output pulses tend to pile up due to high interaction rate of the particles with the detector. Pile-up effects can lead to a severe distortion of the energy and timing information. Pile-up events are conventionally prevented or rejected by both analog and digital electronics. However, for decreasing the exposure times in medical imaging applications, it is important to maintain the pulses and extract their true information by pile-up correction methods. The single-event reconstruction method is a relatively new model-based approach for recovering the pulses one-by-one using a fitting procedure, for which a fast fitting algorithm is a prerequisite. This article proposes a fast non-iterative algorithm based on successive integration which fits the bi-exponential model to experimental data. After optimizing the method, the energy spectra, energy resolution and peak-to-peak count ratios are calculated for different counting rates using the proposed algorithm as well as the rejection method for comparison. The obtained results prove the effectiveness of the proposed method as a pile-up processing scheme designed for spectroscopic and medical radiation detection applications.

1. Introduction

Pulse pile-up phenomenon occurs in high-count-rate radiation detection experiments where two or more subsequent electric pulses overlap due to finite resolving time of the detector [1,2]. The pile-up effect not only deteriorates the energy [3] and timing [4] resolution, but can also distort the spatial resolution in nuclear medicine imaging modalities like Positron Emission Tomography (PET) and Single Photon Emission Computed Tomography (SPECT) [5]. Different strategies exist to solve this problem such as rejection methods (discarding all pile-up events) [6–8], prevention methods (optimally shaping the pulses to minimize their probability of overlapping [9,10]) and correction algorithms (separating the piled-up pulses [1,11,12]).

Since the rejection methods may lead to a substantial decrease of the detector throughput at higher rates, the data acquisition time must be increased to obtain an acceptable count with tolerable statistical noise [13]. However, a longer exposure time means a higher radiation dose for patients in medical imaging procedures.

A shaping method mainly aims to reshape the slow decaying pulses of the preamplifier for removing their long tails in order to avoid the pile-up effect [14]. Although digital triangular and trapezoidal shapers are now frequently implemented and used [15–17], the shaping methods may fail to preserve the original pulse amplitude (energy information) at high counting rates, resulting in degradation of the energy resolution and Signal-to-Noise Ratio (SNR) [18].

Pile-up correction approaches are relatively recent, especially facilitated by the advent of digital processing modules [19,20]. Most of the correction methods consider the pile-up pulse waveform as a linear combination of single events with a determined pulse model but unknown amplitudes and times of arrival [1,11,21,22]. However, for further simplifying the problem, the time of arrival is usually obtained by a popular method like leading edge detection [5,23] or constant fraction discrimination [24]. Pulse model can be determined experimentally by inspecting a set of detector output pulses [21,25]; or can be a mathematical description of the physical processes of the pulse formation and collection [1,5,22,26], for instance the so-called bi-exponential model [19,22].

The main drawbacks of pile-up correction strategies are: (a) their high complexity and computational costs for high order pile-up cases, and (b) the need for determining model parameters beforehand, except for the amplitudes which must be computed. Although the fixed predetermined parameters may be admissible for all pulses of a scintillator, they may drastically change for the detectors with large variations in charge collection time (due to different depths of interaction), resulting

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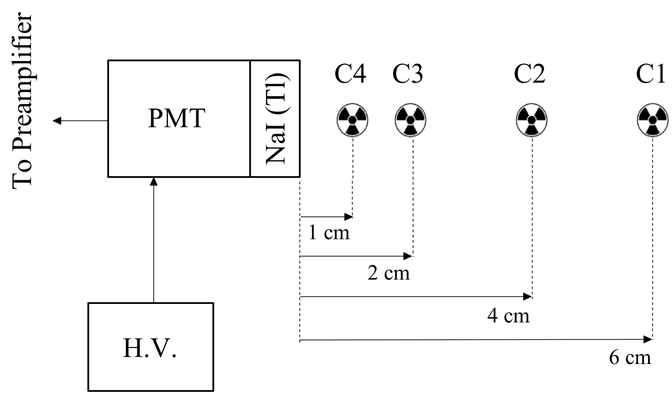

Fig. 1. The Cs-137 source was placed at different distances of 6, 4, 2 and 1cm from the detector front end to obtain different count rates.

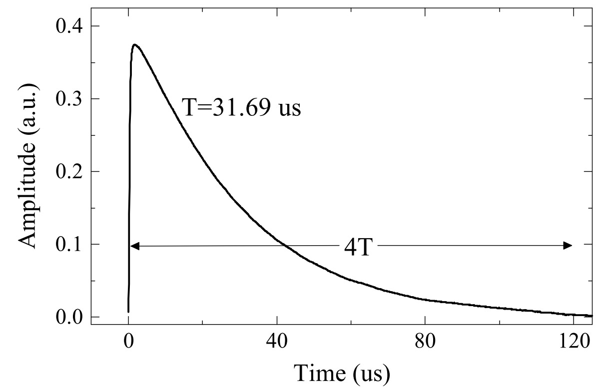

Fig. 2. Mean curve used for determining the pulse length of the system.

in the ballistic deficit effect [23]. Semiconductor and large-volume gas detectors are the best examples for such problem in which the ballistic deficit causes different pulse shapes, even for identical incident particles [27,28].

Single-event reconstruction method [5] recovers each single pulse by subtracting the extrapolated remnants of the previous pulses [19], which can solve both the above mentioned problems. In this method, the times of arrival must be determined beforehand and a pulse model (either experimental [29] or analytical [5,19]) is used for tail extrapolation. Since the pulses are reconstructed one-by-one using an identical procedure, the complexity of the problem does not depend on the pile-up order. The method simplicity allows to determine all the model parameters (not only the amplitude) during the fitting procedure. Therefore, this method can be implemented for semiconductor and gas detectors, too. The common fitting algorithms such as least squares regression suffer from the need for proper start parameters and sufficient iterations which can cause a lot of computational expenses [30,31]. This can be a bottleneck for the single-event reconstruction method.

Present article suggests a simple, accurate and non-iterative algorithm based on successive integration of the pulses for estimating the pulse parameters in a pile-up correction procedure by single-event reconstruction. As an example to illustrate the functionality of the method under realistic conditions, dedicated experimental data at different count rates are generated and analyzed.

2. Materials and methods

2.1. Acquisition of experimental data

An experimental setup provided the actual pulses for evaluating the effectiveness of the proposed method. For this purpose, a Cs-137 radioactive disc source with an activity of 9.15 μCi was placed in front of a NaI(Tl) scintillator coupled with a Photo-Multiplier Tube (PMT). The detector output was connected to a preamplifier. The setup was surrounded by lead bricks as the radiation shielding walls. The preamplifier output pulses are studied in this work, sometimes called "pulses" for brevity. In order to measure at different count rates, the source position was changed with respect to the detector front end according to Fig. 1 which illustrates four cases of C1, C2, C3 and C4 with source-detector distances of 6, 4, 2 and 1 cm, respectively. Preamplifier output pulses were digitized using an InstruStar-ISDS205A oscilloscope card with a rate of 24 Msamples per second (MS/s), and then the data were read out using a personal computer.

2.2. Pulse length determination

For determining the pulse length, a set of 100 pileup-free pulses were obtained from the experimental setup and averaged (see Fig. 2). Decay time constant of the curve (T) was determined by an exponential fitting to the tail of the mean curve: $T = 31.69$ μs, which is nearly equal to the time constant of the preamplifier. In the present work, it is assumed that after 4T, the baseline is restored (actually after 4T, an exponential pulse decays to 1.83% of its initial maximum value). Therefore, a pulse length of $\tau = 4T \approx 120$ μs was finally determined which is equivalent to approximately 3000 samples from the time of arrival of the pulse.

In this work, high-count-rate situations are described in terms of duty cycle. Duty cycle n is a measure of the severity of pile-up effects, calculated by multiplying the count rate r by the pulse length τ [32]:

$$n = r\tau. \tag{1}$$

This definition indicates that for a constant rate r, duty cycle is the average number of pulses during the time interval τ. Note that for the constant rate r, the probability distribution $p(t)$ to have a pulse after the time t follows the Poisson statistics [23]:

$$p(t) = re^{-rt}. \tag{2}$$

Therefore, the probability P to have at least one additional pulse during the pulse length τ is:

$$P = \int_0^{\tau} p(t)dt = 1 - e^{-r\tau} = 1 - e^{-n}. \tag{3}$$

In other words, P is the probability to have a pile-up. For $n = 0.1$, we get the pileup probability of approximately 10%. Based on it, the duty cycle greater than 0.1 is usually identified as high count rate [23,28]. Here, the relatively long time constant of the preamplifier allows to have a large pulse length. Therefore, high rates could be simply achieved without the need for expensive high-activity radiation sources and without loss of generality of the method.

2.3. Proposed method

Single-event reconstruction method needs a model for recovering the remnant tail of each piled-up pulse using the data samples between the times of arrival of the pulse under study and the next one. Different physical reasons such as the type of particle and detector and the electronic chain for pulse collection and amplification, as well as mathematical/statistical considerations like computational costs, goodness-of-fits and the bias-variance compromise may affect the final decision about the proper model. For characterizing the preamplifier output pulses generated from a NaI(Tl) detector, a two-component bi-exponential model is a suitable choice which takes into account both the rate constants of the preamplifier, θ_1 and the processes before the preamplifier (including the scintillator decay constant, anode circuit characteristics and the anode-preamplifier coupling), θ_2 [19]:

$$V_i = A\left(\exp\left(-\theta_1 i\right) - \exp\left(-\theta_2 i\right)\right) \tag{4}$$