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Optimal design of waveform digitisers for both energy resolution and pulse shape discrimination

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A R T I C L E I N F O

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A B S T R A C T

Fast digitisers and digital pulse processing have been widely used for spectral application and pulse shape discrimination (PSD) owing to their advantages in terms of compactness, higher trigger rates, offline analysis, etc. Meanwhile, the noise of readout electronics is usually trivial for organic, plastic, or liquid scintillator with PSD ability because of their poor intrinsic energy resolution. However, $LaBr_3$(Ce) has been widely used for its excellent energy resolution and has been proven to have PSD ability for alpha/gamma particles. Therefore, designing a digital acquisition system for such scintillators as $LaBr_3$(Ce) with both optimal energy resolution and promising PSD ability is worthwhile. Several experimental research studies about the choice of digitiser properties for liquid scintillators have already been conducted in terms of the sampling rate and vertical resolution. Quantitative analysis on the influence of waveform digitisers, that is, fast amplifier (optional), sampling rates, and vertical resolution, on both applications is still lacking. The present paper provides quantitative analysis of these factors and, hence, general rules about the optimal design of digitisers for both energy resolution and PSD application according to the noise analysis of time-variant gated charge integration.

1. Introduction

The $LaBr_3$(Ce) scintillator has been widely studied for gamma-ray spectroscopy owing to its excellent energy resolution (<3% at 662 keV), detection efficiency, and time resolution. In addition, $LaBr_3$(Ce) has been proven to have the ability for pulse shape discrimination (PSD) between alpha and gamma events [1,2]. The PSD ability extends the application of $LaBr_3$(Ce) for low-activity measurement by distinguishing the alpha contamination from ^{227}Ac (energy >1.6 MeV). Consequently, the design of an acquisition system for $LaBr_3$(Ce) with simultaneous optimal energy resolution and promising PSD ability is worthwhile.

With regards to the PSD, it has been significantly improved owing to the development of fast digitisers during the past years. Several research studies on the influence of digitisers on the PSD performance in organic [3–5], plastic [6], or liquid [7,8] scintillators have been conducted. Recently, McFee et al. [9] studied the PSD performance and energy spectrum application using digitised lanthanum halide scintillator pulses. However, optimal results were not achieved, which was assumed to be due to the degradation of the digitiser. Therefore, research works through quantitative analysis of the influence of digitisers on the energy resolution and PSD remain limited, which should be necessary to provide a general rule about the optimal design of waveform digitisers for specific applications. The present study quantitatively analysed the influence of digitiser properties in terms of fast amplifiers, sampling rate (F_s), and vertical resolution on the spectral resolution and PSD performance. According to the quantitative analysis, sufficiently good energy resolution and PSD performance can be achieved using a moderate digitiser for $LaBr_3$(Ce). Furthermore, this analysis also provides a general rule about the optimal design of waveform digitisers for similar applications based on digital waveform processing.

2. System model and noise analysis of gated integration

A general digital waveform sampling system for scintillators is shown in Fig. 1, where the scintillator is usually coupled to a photomultiplier tube (PMT). The digitiser consists of a fast amplifier, an analogue-to-digital converter (ADC), and other modules responsible for data transfer or storage. The fast amplifier functions as a signal-amplification and/or anti-aliasing filter, which tunes the input signal to obtain a better signal-to-noise ratio (SNR), whereas the ADC is responsible for the digitisation.

In the following discussion, we will focus on the noise analysis of how the fast amplifier and ADC influence the energy resolution and PSD ability (the data transfer and storage are considered negligible).

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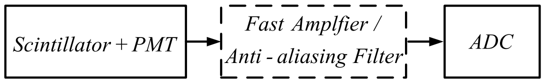

Fig. 1. Digital waveform sampling system for scintillators.

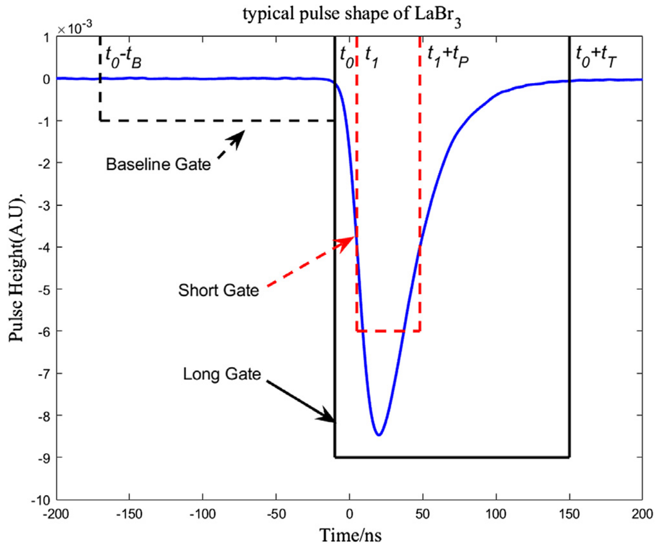

Fig. 2. Gated charge integration.

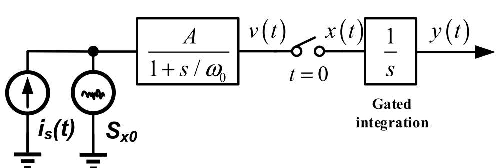

Fig. 3. Analogue diagram of gated charge integration.

Fig. 2 shows that the total integration (long gate) of the current waveform corresponds to the total energy deposited in the scintillator. The charge comparison method (CCM, also called gated integration) is most widely used in PSD and has been proven to be a good method for the PSD in a $LaBr_3$(Ce) detector [1,2]. The PSD feature can be expressed as

$$CCM = \frac{Q_p}{Q_t} = \frac{Short\ Gate\ Integration}{Long\ Gate\ Integration} \tag{1}$$

In this study, methods based on gated charge integration are quantitatively analysed, and hence, the influences of digitisers on both energy resolution and PSD application are classified.

2.1. Noise analysis of gated integration in a simplified analogue domain

Considering a traditional analogue integration, a simplified system response diagram that uses a one-order low-pass filter as a representation of a fast amplifier is shown in Fig. 3.

The measured gated charge integration is composed of the signal and noise of the digitisers, that is,

$$\begin{aligned} Q_m &= \int_0^t \left(x_s(\tau) + x_n(\tau)\right) d\tau \\ &= Q_s + Q_n \end{aligned} \tag{2}$$

The detailed inference can be referred in Ref. [10]. As a simplified inference, the autocorrelation of the input noise is expressed as

$$R_{xx}\left(t_1, t_2\right) = A^2 \cdot S_{x0} \frac{\omega_0}{4} e^{-\omega_0 |t_1 - t_2|}. \tag{3}$$

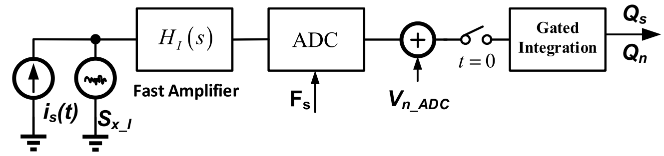

Fig. 4. Digital diagram of the gated charge integration.

The autocorrelation of the output noise of the gated integration can be expressed as

$$R_{yy}\left(t_1, t_2\right) = h\left(t_1\right) * R_{xx}\left(t_1, t_2\right) * h\left(t_2\right), \tag{4}$$

where the impulse response of the gated integrator is $h(t) = 1$. Therefore, the uncertainty of the gated integration caused by the noise can be calculated as

$$\begin{aligned} \sigma_y^2(t) &= E\left[y(t)\, y(t)\right] = R_{yy}\left(t_1, t_2\right)|_{t_1 = t_2 = t} \\ &= A^2 \cdot \frac{S_{x0}}{2}\left(t - \frac{1}{\omega_0} \cdot \left(1 - e^{-\omega_0 t}\right)\right) \end{aligned}. \tag{5}$$

If gated integration time is much bigger than the time constant of fast amplifier, that is $t \gg 1/\omega_0$, which is normally satisfied, the uncertainty of the integrated charge caused by the noise can be simplified as

$$\sigma_y^2(t) \approx A^2 \cdot \frac{S_{x0}}{2} \cdot t. \tag{6}$$

By normalising with current-to-voltage (I–V) gain A, the input-referred uncertainty of the gated charge caused by the noise is expressed as

$$\sigma_{Q_n}^2(t) \approx \frac{1}{2} S_{x0} \cdot t. \tag{7}$$

2.2. Noise analysis of the gated integration in a digital domain

In the discrete digital domain, the analogue integration will be replaced by the sum of the digital data, and the system diagram is shown in Fig. 4.

The measured gated charge integration can be expressed as

$$\begin{aligned} Q &= \sum_k \left(i_s(k) + i_n(k)\right) \cdot T_s \\ &= Q_s + Q_n \end{aligned}. \tag{8}$$

The noise is usually considered as independent of the signals. Thus, the uncertainty of Q_n can be expressed as

$$\sigma_{Q_n}^2 = T_s^2 \cdot \sum_j \sum_k \operatorname{cov}\left[i_n(j), i_n(k)\right]. \tag{9}$$

Fig. 4 shows that the noise mainly consists of two parts: fast amplifier and ADC noise. We need to mention that the noise from ADC can be normally considered uncorrelated in most situations, whereas the noise from the fast amplifier is usually band-limited, which is correlated. In the next two subsections, we will separately present their analysis, although we will end up with the same formula, that is, Eq. (7).

2.2.1. Analysis of uncorrelated noise from ADC

All ADC internal circuits produce a certain amount of broadband, that is, an uncorrelated noise due to the resistor and 'kT/C' noises, which is normally called *input-referred noise* (V_{ir}). Meanwhile, some correlations exist between the quantisation error (V_q) and the input signal, especially if the input signal is an exact sub-multiple of the sampling frequency. In other words, the total noise of the ADC can be expressed as follows:

$$V_{n\_ADC} = \sqrt{V_{ir}^2 + V_q^2}. \tag{10}$$