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Influence of sampling properties of fast-waveform digitizers on neutron – gamma-ray, pulse-shape discrimination for organic scintillation detectors

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ABSTRACT

One of the most important questions to be answered with regard to digital pulse-shape discrimination (PSD) systems based on organic scintillators is: What sampling properties are required for a fast-waveform digitizer used for digitizing neutron/gamma-ray pulses, while an accurate PSD is desired? Answering this question is the main objective of this paper. Specifically, the paper describes the influence of the resolution and sampling frequency of a waveform digitizer on the PSD performance of organic scintillators. The results presented in this paper are meant to help the reader choosing a waveform digitizer with appropriate bit resolution and sampling frequency. The results presented here show that a 12-bit, 250-MHz digitizer is a good choice for applications that require good PSD performance. However, when more accurate PSD performance is the main requirement, this paper presents PSD figures of merit to qualify the impact of further increasing either sampling frequency or resolution of the digitizer.

1. Introduction

Accurate detection of neutrons is required in many research and industry areas. Examples are nuclear nonproliferation, reactor instrumentation, particle physics, material science, dosimetry, and astrophysics [1]. Generally, two neutron-detection-media types are available for neutron-detection systems: the first type is (strongly) sensitive to neutrons while highly insensitive to other radiation types (gamma-ray background is a typical example); the second medium type is sensitive to various radiation particles simultaneously and an additional data processing is needed after the raw data have been acquired. For the first, He-3 is a frequently used neutron-detection medium [1]. For the latter, organic scintillators are a good example; they have been used for several decades and their performance has been characterized in detail [2,3]. Organic scintillators, when used in mixed neutron/gamma-ray fields (the case of any field environment), are sensitive to both particle types; therefore, neutrons and gamma rays have to be accurately discriminated. The discrimination algorithm, such as pulse-shape discrimination (PSD), needs to be optimized to achieve the full discrimination potential of the chosen organic scintillator.

Neutron and gamma-ray PSD using organic scintillation detectors is a widely adopted technique in fields such as nuclear nonproliferation, international safeguards, nuclear material control and accountability, and national security. Other examples of areas where an accurate PSD is needed are dosimetry and reactor instrumentation [4]. In contrast to thermal neutron detectors (such as He-3-based detection systems), organic scintillators are able to detect high-energy (fast) neutrons via elastic-scattering collisions and do not require the presence of a moderating material. Therefore, their time response is significantly better than that of a detector utilizing neutron moderation [1]. The organic scintillators are also sensitive to gamma rays; this characteristic makes them suitable for measurements in mixed neutron/gamma-ray fields, especially when the detection application requires a simultaneous detection of neutrons and gamma rays. A large number of papers were published on PSD performance of liquid scintillators [5–10]. Because of the background gamma-ray presence the accurate neutron detection in a field environment requires accurate discrimination of neutrons from gamma rays. This is especially important for applications where fast and robust detection systems are paramount, such as nuclear nonproliferation and safeguards. In the past, characteristics of digital PSD systems were described and discussed [11–13] and the results indicate that there is an advantage of using digital over analog PSD systems. Specifically, the advantages include the automation of critical PSD parameters, adaptive data processing, multifunction operation,

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maximum throughput, reduced system's size, and straightforward upgrading/reprograming [14].

For areas such as nuclear nonproliferation, fast and robust methods for the identification of special nuclear material (SNM), and medical and industrial radiation sources are needed. The identification of SNM and other sources with organic scintillators using fast-waveform digitizers is one of many approaches researched in the past [15]. In nuclear nonproliferation applications, accurate discrimination of neutrons from gamma rays significantly influences the outcome of material identification/characterization. Specifically, particle misclassification can lead to longer measurement times needed or even to false identification/misclassification of measured material. With recent developments in the area of fast-waveform digitizers it is foreseen that the digital PSD will eventually replace analog PSD systems in several applications due to their simplicity, versatility, and accuracy. Therefore, the most important question to be answered before replacing the analog PSD technology for organic scintillators is: What sampling properties are required for the fast-waveform digitizers when used in conjunction with organic scintillators used in mixed neutron/gamma-ray fields? Answering this question is the main objective of this publication. Higher sampling frequency and resolution will always improve PSD. However, commercially available digitizers will tradeoff speed for resolution, leaving one to choose between higher speed or higher resolution. Digitizers that achieve both high-speed and high resolution are costly. They can also have a ripple effect in the PSD system, such as requiring more processing power and memory for recorded pulses. Therefore, it is economical to select the minimum requirements for a target PSD performance. In addition, a quantitative comparison of the PSD performance of different digitizers is discussed to provide details about how the sampling properties of waveform digitizers influence the PSD performance and what performance improvement should be expected after increasing the digitizer's sampling properties from a ‘reference level’. Two quantitative comparisons are discussed: one from the ‘nuclear-measurements’ point of view, based on a figure of merit (FOM) describing the physical separation of neutrons from gamma rays, and another from the ‘signal-to-noise-ratio’ point of view, focused on analyzing the signal-sampling process during the data acquisition.

In this paper, various fast-waveform digitizers are compared and their PSD performance is assessed. Specifically, the PSD performance of a ‘reference’ 12-bit, 250-MHz waveform digitizer is compared to that of 10-bit–1-GHz, 10-bit–2-GHz, and 14-bit–400-MHz digitizers.

2. Comparison of waveform digitizers from PSD-performance standpoint

2.1. Description of waveform digitizers

The Detection for Nuclear Nonproliferation Group (DNNG) at the University of Michigan uses various fast-waveform digitizers for research and education. In this work, the following digitizers are compared to assess their PSD performance:

– CAEN V1720, 12-bit, 250-MHz, 2-Volt range, effective number of bits (ENOB) = 10.14 bits
– CAEN V1751, 10-bit, 1-GHz, 1-Volt range, ENOB = 9.04 bits
–CAEN V1751, 10-bit, 2-GHz, 1-Volt range, ENOB = 9.04 bits
– XIA Pixie-400, 14-bit, 400-MHz, 2-Volt range, ENOB = 11.2 bits

The PSD performance of the digitizers was investigated with an EJ-309 liquid scintillation detector. This detector is based on a 7.62-cm diameter, 7.62-cm thick EJ-309 sealed liquid cell attached to an ETL9821B photomultiplier. All PSD results reported in this paper were obtained by processing measured data in an off-line mode. It needs to be noted that the V1751's dynamic range is only 1 V; therefore, the digitizers were compared at this dynamic range. As the result, when comparing the digitizers the ENOB values for digitizers with a 2-V range need to be lowered by one.

2.2. Charge-integration PSD method

This section describes the PSD method used to evaluate the digitizers in this paper. A charge-integration PSD method was used; the digital version of this PSD method was optimized in the past [16]. Each pulse was integrated from the beginning of the pulse to an optimized end point in the tail. This integral is referred to as the total integral. The second integral was taken from an optimized starting position after the pulse maximum (20 ns after pulse maximum) to the same ending point as was used for the total integral (800 ns after pulse maximum). This integral is referred to as the tail integral. Generally, the tail integral of a neutron pulse is larger than that of a gamma-ray pulse with the same total integral value. This property is due to a larger fraction of delayed scintillation light produced by heavier particles; this light contributes to the tail of a pulse. The gamma rays interact (produce light) through electrons (Compton scattering) in the scintillation material while the neutrons interact mostly through protons (elastic scattering) [1]. Fig. 1 shows a typical PSD plot in which calculated tail and total integrals are depicted. The identical PSD parameters were used for all digitizers under investigation; the optimal PSD parameters do not depend on the sampling characteristics of the digitizers, unless a digitizer with significantly worse sampling properties would be used.

2.3. Initial measurements

In order to test the functionality of the digitizers and to create and optimize data-processing software, PSD data were initially acquired for a Cf-252 source (~11,000 spontaneous fissions per second) placed at 15 cm from the face of an EJ-309 liquid scintillation detector. The measurement threshold was set to 80 keVee. Fig. 2 shows the EJ-309 detector with the Cf-252 source.

Figs. 1 and 3 show PSD results for the CAEN digitizers (V1720 and V1751 in 1-GHz mode). To directly compare the PSD results two FOMs described in Fig. 4 and Eqs. 1 and 2 were used.

For each accepted waveform (clipped waveforms are not accepted as their peaks are deformed by the presence of dynamic-range limits of the digitizers), a ratio of tail and total integrals is calculated.

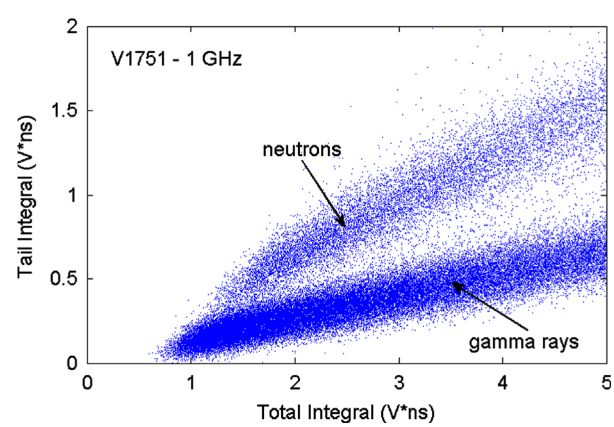

Fig. 1. Tail versus total integral of measured pulses with a 7.62-cm by 7.62-cm EJ-309 detector and a Cf-252 source at a threshold of 80 keVee (80 keV electron equiv.). Each point represents one measured waveform (either gamma ray or neutron).

The FOMs are based on assessing the separation of neutron and gamma-ray peaks in tail/total integral ratio histograms and the overlap between the peaks. Specifically, the 'FOM_{FWHM}' is calculated from the distance between the peaks and their FWHM values, while the 'FOM_{valley}' is calculated from the distance between the peaks and the height of the valley between the peaks (overlap height). The overlap height is normalized to the neutron-peak height to allow for comparison of two histograms with non-identical count integrals. The peaks and the valley are fitted with 4th-order polynomials. It needs to be noted that the FOM_{FWHM} is significantly less sensitive than the FOM_{valley}. This fact is shown in the following section where the FOM results are discussed.

$$\mathrm{FOM_{FWHM}} = \frac{D}{(\mathrm{FWHM}_g + \mathrm{FWHM}_n)} \tag{1}$$

$$\mathrm{FOM_{valley}} = \frac{D \times H_n}{H_{\mathrm{valley}}} \tag{2}$$

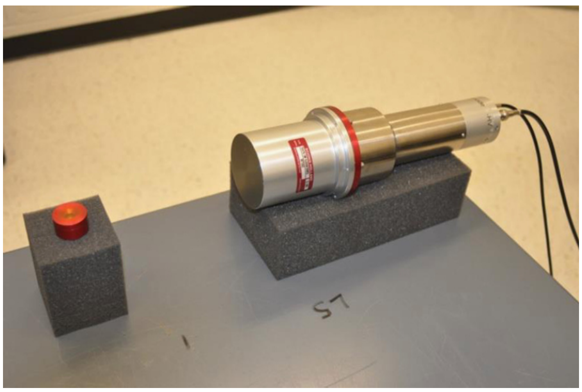

Fig. 2. 7.62-cm by 7.62-cm EJ-309 liquid scintillation detector in conjunction with a Cf-252 source used for the investigation on the PSD performance of various digitizers.

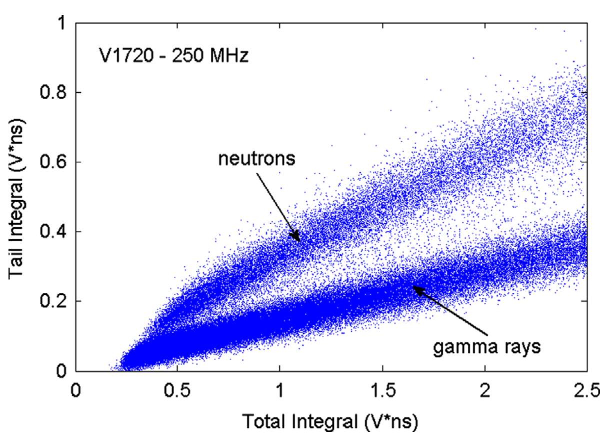

Fig. 3. PSD result for V1720 and 7.62-cm by 7.62-cm EJ-309 detector with Cf-252. The measurement threshold was set to 80 keVee.

2.4. Direct comparison of fast-waveform digitizers

For the direct comparison of the PSD performance of the digitizers, the Cf-252 source was placed 18 cm from the faces of the EJ-309 detector. For each experimental setup (each detector in combination with each digitizer) approximately 10^7 waveforms were collected to minimize statistical fluctuations of the FOM results. The measurement threshold was set to 80 keVee.

Figs. 5–8 show the FOM results for the 7.62-cm by 7.62-cm EJ-309 detector at a threshold of 80 keVee. Fig. 5 shows the 'reference' result (data measured with V1720) and the FOM percentages shown in Figs. 6–8 are calculated relative to the V1720 result. Both FOMs are compared. The results clearly show that the 14-bit, 400-MHz digitizer provides the best PSD results. Specifically, the PSD results are higher by approximately 83% (FOM_{Valley}) and 16% (FOM_{FWHM}) relative to the 12-bit, 250-MHz digitizer. Table 1 summarizes the FOM results.

Results in Table 1 show that the FOM_{valley} is more sensitive than the FOM_{FWHM}, which is caused by the strong sensitivity of the valley height to the measurement setup. The FOM_{valley} is considered a more representative quantity to describe the physical separation of neutrons from gamma rays as the valley between the distributions is the most important measure of the PSD quality.

The results indicate that the 14-bit–400-MHz resolution combination leads to the best PSD results among the investigated waveform digitizers. The results also show that a 10-bit digitizer can perform better than a 12-bit digitizer, if the 10-bit digitizer has a significantly better time resolution. Finally, 2-GHz sampling rate can be used to significantly improve the PSD performance, for the 10-bit resolution. In the following section we will further discuss these results from the signal-to-noise-ratio point of view.

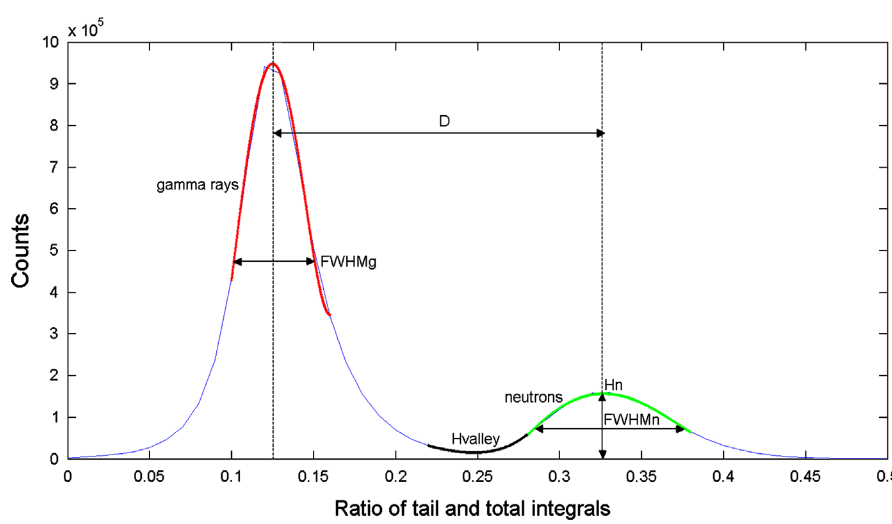

Fig. 4. Definitions of FOMs used for comparing PSD performances of waveform digitizers.

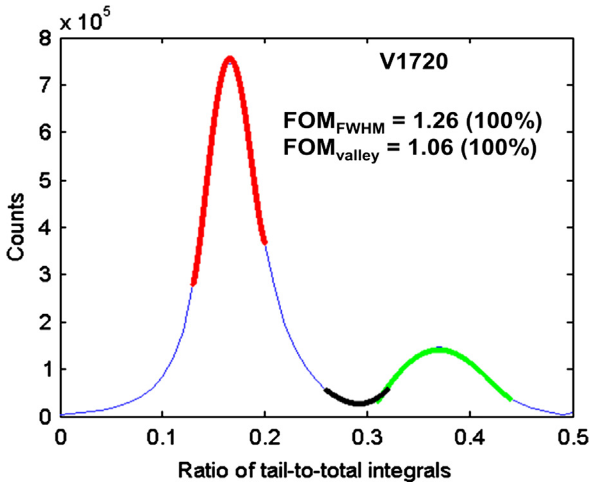

Fig. 5. FOMs calculated from the data acquired with the 12-bit, 250-MHz digitizer, the 7.62-cm EJ-309 detector, and the Cf-252 source. The measurement threshold was set to 80 keVee.

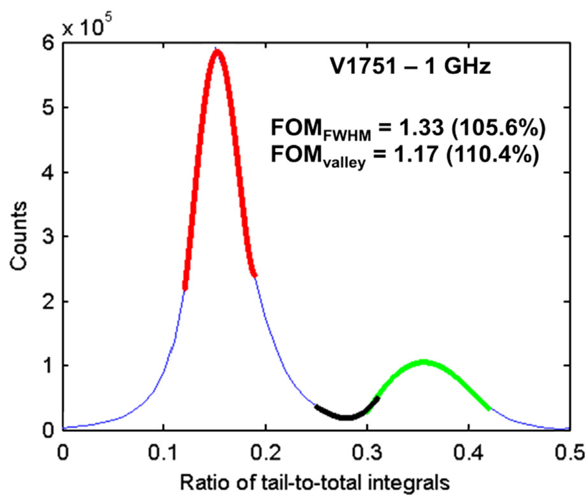

Fig. 6. FOMs calculated from the data acquired with the 10-bit, 1-GHz digitizer, the 7.62-cm EJ-309 detector, and the Cf-252 source. The measurement threshold was set to 80 keVee.

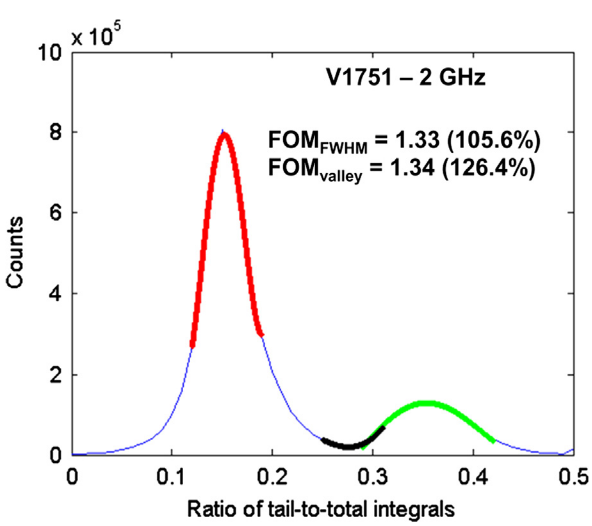

Fig. 7. FOMs calculated from the data acquired with the 10-bit, 2-GHz digitizer, the 7.62-cm EJ-309 detector, and the Cf-252 source. The measurement threshold was set to 80 keVee.

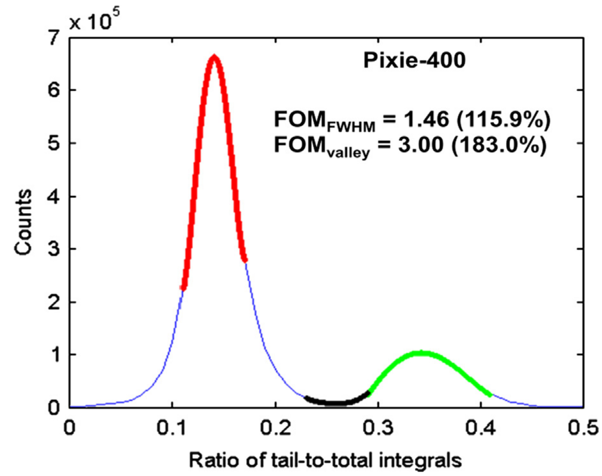

Fig. 8. FOMs calculated from the data acquired with the 14-bit, 400-MHz digitizer, the 7.62-cm EJ-309 detector, and the Cf-252 source. The measurement threshold was set to 80 keVee.

Table 1
Summary of FOM results for the digitizers under investigation.

Digitizer model	ENOB for 1-V range	Sampling frequency (MHz)	FOM_{FWHM}	FOM_{valley}
V1720	9.14	250	1.26	1.06
V1751	9.04	1000	1.33	1.17
V1751	9.04	2000	1.33	1.34
Pixie-400	10.2	400	1.46	3.00

3. Study of digitizer resolution and sampling frequency

In this section, the influence of the resolution and sampling frequency are described from the signal-processing standpoint. Specifically, the relationship between PSD and the digitizer sampling rates and resolution is discussed in the following sections.

3.1. Digitization process and minimum sampling frequency

For the benefit of readers not familiar with the sampling of digitizers, this section gives a basic tutorial of the signal-digitization process. An analog-to-digital (ADC) converter at the input of a waveform digitizer converts a continuous analog voltage waveform to digital binary numbers that 'represent' the original analog signal. An ADC quantizes and samples the continuous voltage periodically (with a constant sampling time step) and the ADC output is a discrete-time and discrete-amplitude digital waveform.

The resolution of an ADC relates to the number of discrete digital values it can produce over the range of analog voltage values. It is expressed in terms of bits (N), and the number of levels in an ADC is 2^N. For example, an ADC with 10 bit resolution has 1024 levels, and the input voltage can have any value between 0 and 1023. A number of non-idealities such as quantization error, clock jitter and intrinsic circuit non-linearities affect the quality of the resulting digital signal. These non-idealities result as spurs and noise at the ADC's output; therefore, they degrade the signal-to-noise ratio (SNR) of the output which in turn reduces the ENOB of the ADC. Moreover, the maximum possible sampling rate of the ADC determines the highest frequency that can be reliably digitized (captured). The sampling frequency of the ADC must be at least twice as much as the highest frequency of interest. For example, if a 125 MHz signal is to be digitized, then the minimum sampling rate of the ADC must be 250 MS/s [17].

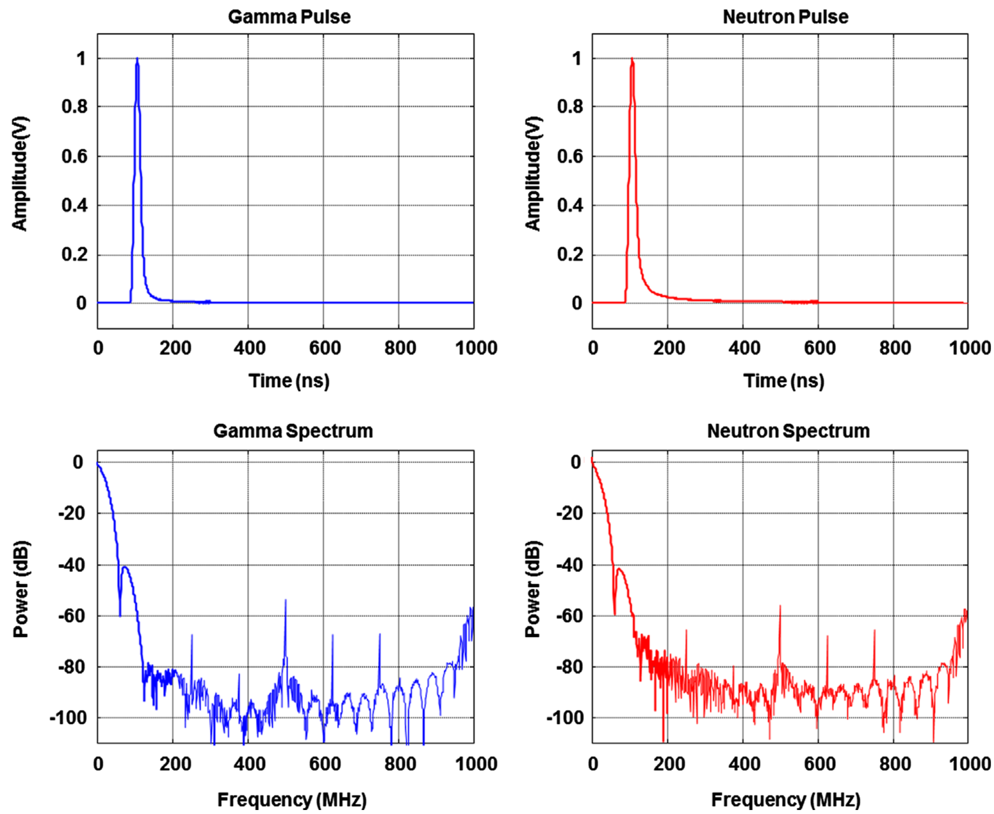

Fig. 9. Averaged gamma-ray and neutron pulses and their frequency spectra. The digital charge-integration PSD method described in Section 2.2 was used to discriminate neutrons from gamma rays. The noise floor is below −80 dB.

In order to determine the minimum sampling frequency required to correctly capture gamma-ray and neutron pulses, we performed a fast Fourier transform (FFT) on pulses captured with a digitizer with a relatively high sampling rate (2 GS/s). Fig. 9 shows the spectrum of averaged neutron and gamma-ray pulses (20,000 measured pulses averaged), and it is clear that majority of the 'pulse power' is spread over frequencies below 120 MHz, and any digitizer with sampling rate above 240 MS/s will capture the pulses with good spectral integrity. Moreover, the frequency spectrum of some individual pulses without pulse averaging is presented in Fig. 10. This figure again shows that the majority of the power is spread over frequencies below 120 MHz. In addition, the noise floor is higher than the averaged plots in Fig. 9, which is expected because of the pulse averaging attenuating random noise.

3.2. Simulations and performance metric

Extensive simulations were conducted to study the impact of digitizer resolution on the quality of PSD. In this section, the simulation setup is described. First, a large number of pulses were measured with a 2 GS/s digitizer and discriminated using the digital PSD method described in Section 2.2. Next, a large number of pulses (~20,000 pulses) were averaged to produce 'high-resolution' gamma-ray and neutron pulse templates. Averaging a large number of pulses suppresses the random noise and increases the effective resolution of the pulses. The next step was to quantize and down-sample the pulses to simulate their digitization with a lower sampling frequency and/or lower bit resolution. After that, Gaussian white noise was added to the pulse to mimic random noise that pulses may experience in the electronics and PMTs. Finally, PSD was performed again on the pulses. 20,000 iterations of the above mentioned steps were performed and the probability of incorrectly classified pulses was recorded once the iterations for a given resolution were complete. Fig. 11 illustrates the details of the simulation setup.

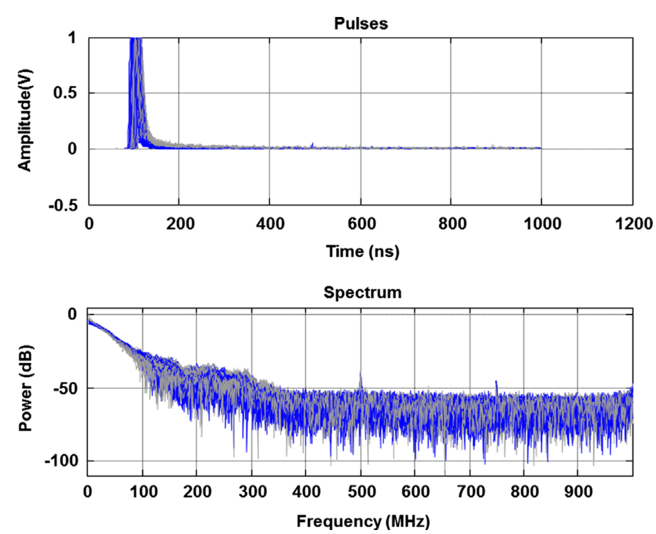

Fig. 10. Gamma-ray and neutron pulses with their frequency spectra. No pulse averaging was performed, which results in a significantly higher noise floor (< −50 dB) than in Fig. 9 where pulse averaging was used (< −80 dB).

Extensive simulations were conducted in order to study the effect of resolution on the quality of PSD. The performance metric used to measure the quality of PSD is the probability of misclassification of a given pulse. In other words, if the tail/total integral ratios for gamma rays and neutrons overlap, it would be impossible to differentiate between the types of particle. Fig. 12 illustrates how the probability of pulse misclassification is computed in simulation. The tail/total integral ratios for the quantized gamma-ray and neutron pulses for a

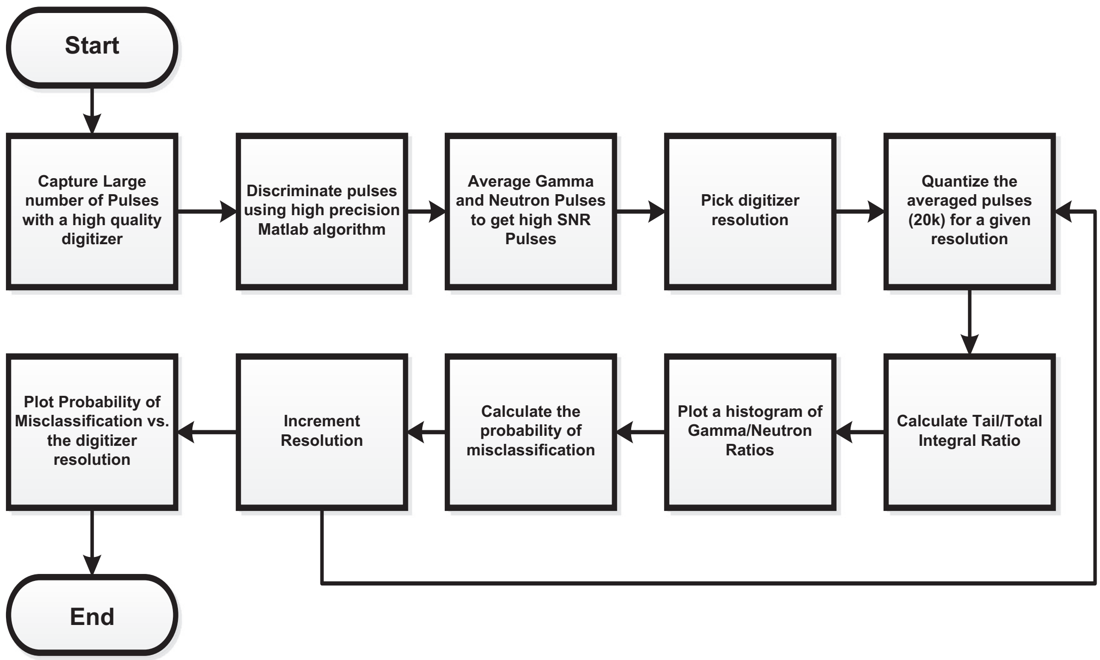

Fig. 11. Simulation setup.

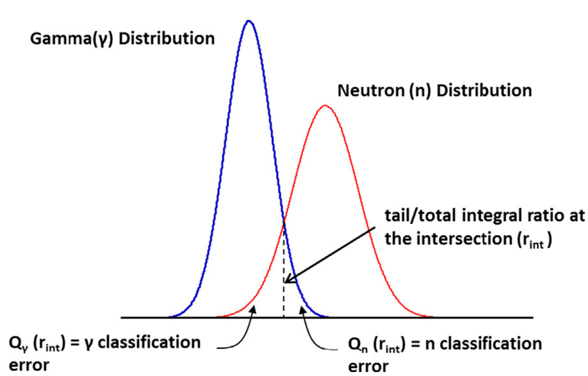

Fig. 12. Definition of probability of misclassified pulses.

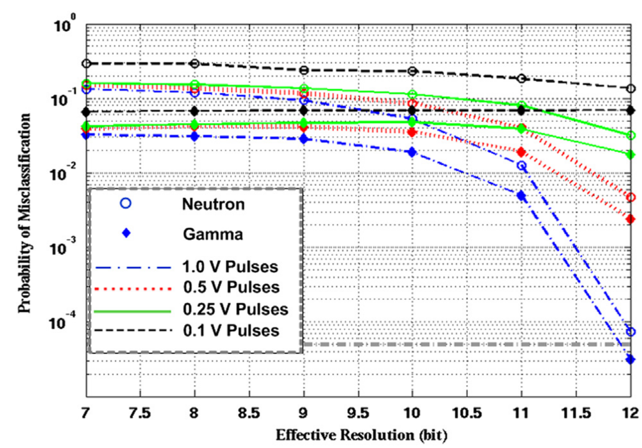

Fig. 13. Probability of particle misclassification versus effective resolution of the digitizer. The dash line represents the limit of the simulation. Any value below 1/20,000 should be rejected; 20,000 pulses were measured.

given resolution are fit to Gaussian distributions. Typically, the Gaussian curves overlap, as depicted in Fig. 12, which represents the region of misclassification. The probability of a pulse being misclassified can be computed using the Q function for each of those distributions which represent the probability of misclassification.

3.3. Digitizer resolution versus PSD performance

In order to study the effect of quantization (ADC resolution) on the PSD, the amplitude of the pulses being studied must be fixed since the effective resolution is a function of the pulse amplitude. In other words, an ADC effective resolution is often quoted at the peak voltage swing, and any signal with a less than the maximum possible voltage swing will be digitized with an effective resolution lower than the full swing resolution. For example, an ADC with ENOB = 14 and 1-V dynamic range will only be 14 bits if the input is a 1-V pulse. A 0.5-V pulse will experience a 13-bit resolution in the same ADC. Therefore, the PSD quality (probability of misclassification) was studied at a set of fixed pulse amplitudes.

Fig. 13 shows the probability of misclassified pulses as a function of digitizer resolution. In order to study the isolated effect of digitizer resolution on PSD, the energy of the pulses was fixed and four different voltage levels (1 V, 0.5 V, 0.25 V, and 0.1 V) were investigated. Fig. 13 shows that the error rate for 100-mV pulses is the highest, while 1-V pulses have the lowest error rate. If the probability of misclassification for a given application is known, Fig. 13 can be used as a means of selecting the required digitizer resolution. One can traverse along the curves in Fig. 13 to pick the digitizer resolution at a given energy for a required probability of error. For example, if 1-V pulses are to be correctly discriminated with one in a thousand errors, then a 12-bit digitizer with 1-V dynamic range and sufficient sampling frequency (>240 MHz) can be used.

3.4. Final discussion—improving resolution by oversampling

High-resolution digitizers exhibit lower quantization noise and therefore the SNR of the captured signal is higher, leading to a better PSD. Generally, there are two methods to improve SNR. First, as mentioned above, a higher resolution reduces the quantization noise and therefore improves the SNR. In addition, if the signal of interest (e.g. gamma-ray or neutron pulse) is bandlimited, a digitizer with a sampling rate higher than $2f_0$, where f_0 is the bandwidth of the pulse, is considered an oversampling digitizer. Oversampling of the signal also leads to an improved SNR. The total quantization noise power depends only on the resolution of the ADC, and oversampling spreads the noise power over $0.5f_s$, where f_s is the sampling frequency of the ADC. The SNR of the signal is only impacted by the quantization noise that falls within the signal bandwidth. Therefore, oversampling can also lead to PSD improvement. According to [17], the resolution of the ADC can be enhanced by one bit if the signal is oversampled four times. For example, if a 125-MHz pulse is being captured with a 12-bit, 250-MHz ADC, the ADC's resolution can be 'enhanced' to 13 bits if the sampling rate is quadruped (e.g. 1 GHz). This fact supports the observations reported in Section 2.4; the PSD performance of the 10-bit digitizer (ENOB = 9 bits) at 1- and 2-GHz is only slightly better than the PSD performance of the 12-bit, 250-MHz digitizer (ENOB≅10 for 1-V range).

4. Summary and conclusions

This paper describes the influence of the resolution and sampling frequency of a waveform digitizer on the PSD performance of organic scintillators. The results presented in this paper are meant to serve as a guide for choosing a waveform digitizer for PSD-capable organic scintillators. It is concluded that a 12-bit, 250-MHz digitizer is a good choice for applications that require good PSD performance. However, when excellent PSD performance is the main requirement, the user has two choices: (a) significantly increase the sampling frequency to virtually increase the bit resolution—a factor of four increase of the sampling frequency 'mimics' an increase of the bit resolution by one, or (b) when even better PSD performance is needed, also increase the bit resolution to be utilized with a reasonable sampling frequency, e.g. at least 250 MHz. Sections 2.4 and 3.3 provide the readers with a quantitative description for the PSD performance for several bit-resolution/sampling-frequency combinations.

Acknowledgments

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