Comparison of Analog and Digital Pulse-Shape-Discrimination Systems

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Abstract

Pulse shape discrimination (PSD) performance of two optimized PSD systems (one digital and one analog) is compared in this work. One system uses digital charge integration, while the other system uses analog zero crossing. Measurements were conducted with each PSD system using the CAEN V1720 (250 MHz) data acquisition system. An organic-liquid scintillator, coupled to a photo-multiplier tube, was used to detect neutrons and gamma rays from a Cf-252 spontaneous-fission source. The PSD performance of both systems was optimized and quantified using a traditional figure-of-merit (FOM) approach. FOM's were found for three, 300 keVee light-output bins, spanning from 100 to 1000 keVee, and one larger bin from 100 to 1800 keVee. Digital PSD outperformed analog PSD in the lowest light-output bin by approximately 50%, and by 11% for the highest light-output bin.

Keywords: Pulse shape discrimination; analog PSD; digital data processing; organic liquid scintillators

1. Introduction

Scintillators are radiation detectors that create a measurable collection of light photons when a sufficient amount of energy is deposited from radiation [1]. By coupling light-readout electronics – for example, a photo-multiplier tube (PMT) – to the scintillator, the light can be collected and converted into a voltage pulse, allowing for data acquisition/processing. Some types of scintillators, such as organic-liquid scintillators, are sensitive to both gamma rays and neutrons. Additionally, in organic-liquid scintillators the amount of light produced as a function of time differs based on the type of radiation.

Gamma rays interact in the organic-liquid scintillator via Compton scattering, where outer-shell electrons are ejected from their orbitals and ionize hydrocarbon molecules along their tracks. This process creates a collection of light photons with a narrower time distribution in contrast to light-photon distributions created by neutrons [1]. Typically in organic scintillators, neutrons elastically scatter on either hydrogen or carbon nuclei. When colliding with hydrogen, the neutron will either partially or fully transfer its kinetic energy to the nucleus. On the other hand, if the neutron collides with carbon, only a fraction of its energy can be transferred to the nucleus. The recoiled nucleus then ionizes hydrocarbons in its vicinity. This process of light production is inherently slower than light production induced by gamma-ray interactions. This difference between gamma-ray and neutron scintillation-pulse shapes is exploited by pulse-shape-discrimination (PSD) techniques [1-3, 5].

The two general categories of PSD hardware are analog and digital-based systems. Analog PSD typically consists of a module that is designed to perform specific tasks on the voltage pulse from light-readout electronics, using analog circuitry [2, 3]. The zero-crossing PSD technique is one of the traditional approaches to analog PSD. In zero-crossing, the time at which the tail of a pulse crosses a prescribed amplitude threshold (referred to as “zero”), is reported as a voltage, and is used as a PSD parameter. Particle discrimination is achieved by separating particles based on this voltage. This discrimination

technique is relatively easy to implement into analog circuitry and is therefore a typical choice for analog PSD [7].

Another common method of PSD, digital charge integration (DCI), consists of digitizing the voltage pulse from a light-readout electronic and applying integration techniques to the discretized pulse. Digitizing the pulses also allows the user to apply various data-processing techniques, such as removing clipped (larger than the dynamic range of the digitizer) and double (pileup) pulses, before applying the integration techniques. The analog, zero-crossing PSD technique and the charge-integration technique of the digital-PSD approach (referred to in this work as DCI) share the same goal: To differentiate between gamma-ray and neutron pulses based on the inherently different shapes of pulses measured in a PSD-capable organic scintillator. This work compares the PSD performance of the analog and digital PSD approaches, while maintaining almost identical measurement constraints between the two systems during comparison. The motivation behind this work is to assess the PSD performance of optimized digital and analog PSD systems in a direct and reasonably unbiased comparison.

The analog and digital PSD systems compared in this work output the same type of information; a PSD-parameter histogram (PPH). The measured PPH is used to assess the PSD performance. A sample PPH from Cf-252 data is shown in figure 1a. PSD performance constitutes how well the gamma-ray and neutron distributions are separated from each other in the PPH. The actual comparison method used to quantify the PSD performance of both systems is described in section 2.1. Accurately identifying/separating gamma rays and neutrons in mixed-radiation fields can provide valuable information for a number of research disciplines that use PSD-capable scintillators, including reactor instrumentation, dosimetry, nuclear nonproliferation, and nuclear safeguards [1].

Figure 1a: Sample PSD parameter histogram (PPH).

1.1 Description of Analog PSD System

The Mesytec MPD4 system has four channels, each capable of receiving pulses from a single detector [4]. Each pulse is sent through a 6th-order-trapezoidal filter that proportionally increases the full width at half maximum (FWHM) of the pulse [4], followed by a capacitor that integrates the fast component of the pulse from 0 to 20 ns. This integrated value is then reported as a voltage, which is proportional to the energy deposited by the particle that created the pulse. The MPD4 refers to this value as the amplitude of the pulse (AMPL), although it should be emphasized that AMPL is indeed an integral. The time at which the filtered pulse crosses zero is also reported as a voltage, and it is referred to by the MPD4 as the time at zero crossing (TAC). The TAC parameter is used to discriminate between particle type; typically, gamma rays have smaller TAC values than neutrons. A diagram of the MPD4 electronics is shown in figure 2 and sample AMPL and TAC pulses are shown in figure 3.

TAC and AMPL values are reported as the amplitudes of a shaped, approximately 1 μ s-long pulse, created by the MPD4. For every single scintillator pulse accepted by the fixed-threshold setting of the MPD4 (0.07 V) two outputs are created (TAC and AMPL). A scatter plot of TAC and AMPL produces a PSD image showing a cluster of gamma-ray data and a cluster of neutron data. A histogram of TAC values creates a PPH, showing two adjacent and Gaussian-like distributions: one for gamma rays and one for neutrons. The separation of these two distributions serves an assessment of the PSD performance.

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1.2 Description of Digital PSD System

The digital PSD system chosen for comparison consists of integration techniques applied to digitized pulses, where each pulse is integrated twice, using two different ranges. Sample pulses are shown in figure 4. One integral range captures the full pulse. It begins at a fixed position before the pulse maximum and may extend to the last data point of the pulse. This is referred to as the total integral. The second integral is referred to as the tail integral, where the range begins at a fixed position after the pulse maximum and also extends to the last data point chosen in the total-integral range. This is typically the last point in the data acquisition window. A scatter plot of the tail and total integrals for all pulses produces a PSD image, similar to the PSD image created by the analog-PSD system, with identifiable gamma-ray and neutron clusters. Additionally, a PPH can be created using the ratio values between the tail and total integrals, in a similar fashion to the TAC values from the MPD4. Like the analog-based PPH, the digital-based PPH also produces two adjacent and Gaussian-like distributions for both particle types. The separation of these two distributions in the digital PPH is an assessment of the digital-PSD performance.

Figure 4: Sample EJ-309 pulses as digitized by the CAEN v1720 (250 MHz).

2. PSD Comparison Methodology

An EJ-309 organic-liquid scintillator coupled to a PMT was used to detect gamma rays and neutrons from a Cf-252 spontaneous-fission source. The digital and analog PSD systems were optimized (see sections 2.1.1 and 2.2.2 for details) and compared using the CAEN V1720 digitizer. An illustration of the measurement setup is shown in figure 5 (not to scale). A list of the equipment used is shown in table 1.

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Table 1: Measurement equipment.

Item	Model No.	Description
Radiation Source	N.A.	Cf-252
Radiation Detector	EJ-309	12.7 (d) x12.7 (l) cm organic-liquid scintillator
Photo-Multiplier Tube	ETL-9821	Applied a gain of -1260V for all measurements
CAEN Digitizer	V1720	8 Channels, 12 bits, 250 MHz, 4096 Channels
Mesytec NIM	MPD4	Analog PSD unit

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Figure 5: Illustration of measurement configuration.

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2.1. Assessment of PSD Performance

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The performance of the PSD systems compared in this work is measured by their ability to accurately discriminate between pulse types, over a specified energy range, in a given measurement. Figure-of-merit (FOM) studies are used to assess the separation between the distribution of gamma rays and neutrons in the measured PPH. These distributions take the form of a Gaussian, to which Gaussian fits may be applied. FOM (see Equation 1) calculates the separation between the two distributions using the Gaussian peaks and FWHM values. The FOM equation is therefore an attempt to quantify PSD performance by taking into account how well separated the Gaussian peaks are, in addition to how much the two distributions overlap by also looking at their FWHMs. A higher FOM value signifies better PSD performance. The components of Equation 1 are illustrated in figure 1a.

$$FOM = \frac{|Peak_n - Peak_p|}{FWHM_n + FWHM_p} \qquad \text{Eq. 1}$$

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2.1.1. Analog-PSD Optimization

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In order to achieve the best possible analog-PSD performance, the MPD4 required thorough optimization. The settings of the MPD4 can be modified by either the controls on the front panel of the device or by connecting the MPD4 to a computer using a USB connection. The three primary settings of the MPD4 are Walk, Threshold, and Gain. The Walk parameter influences the straightness of the gamma-ray and neutron clusters at lower energies in the PSD image. The Threshold parameter is used as an energy discriminator, and Gain may improve the signal-to-noise ratio in addition to improving the straightness of the PSD image at higher energies.

The Walk, Threshold, and Gain settings were varied in the optimization process of the MPD4. The Threshold parameter was kept at its lowest setting (zero), which corresponds to the fixed energy threshold of the MPD4 (0.07 V). The Walk parameter was then varied, while fixing the Gain parameter at its lowest setting. Using FOM studies on the various walk measurements, an optimal walk setting was found. Following this, the Gain parameter was increased and the influence on the FOM was observed. The optimal MPD4 settings are shown in table 2.

Table 2: MPD4 settings that affect PSD.

Parameter	Value Range	Optimal Value
Walk	[50:1:150]	70
Threshold	[0:1:255]	0
Gain	[0:1:15]	2

2.1.2. Digital-PSD Optimization

Varying the start position of the tail integral optimizes the digital-PSD approach. The optimal tail-integral start time is a function of the detector and PMT used in the measurement, and was found to be 20 ns after the pulse maxima. The total integral began 5 ns before the pulse maxima. Both the tail integral and the total integral range extended through the last point in the measured pulse. It is worth mentioning that the integrals are the sum of the sample values of the pulse and that no interpolations are made between samples.

2.1.3. Energy Calibration

Calibrating the analog and digital PSD systems required careful attention. While the measurement configurations remained the same for both systems, the calibration spectra appear different. This is due to the inherently different output data of the analog and digital PSD systems. Where digital PSD uses the peak amplitude of the pulse to relate back to energy, the MPD4 instead integrates the first 20 ns of a shaped pulse. These values cannot be directly compared until after they have both been individually calibrated to a known gamma-ray source. Cs-137 was used to determine the energy domain corresponding to both systems (figure 6).

Calibration measurements were achieved by equating 80% of the Compton edge in both the AMPL spectrum (analog PSD) and the pulse height spectrum (digital PSD) to 478 keV (the highest gamma-ray energy that may be deposited in a single Compton scattering event of a Cs-137 gamma ray); equivalent to 478 keVee light output. It is worth mentioning that the MPD4 has a fixed voltage threshold of 0.07 V. From the calibrated AMPL distribution, the MPD-4 threshold was found to be 100 keVee. This same threshold was then applied to the digital-PSD system. The measured voltages corresponding to 80% of the Compton edge in both the analog and digital PSD systems are reported in table 3.

Table 3: Cs-137 calibration data (V to keVee conversion).

	Energy (keV)	Light Output (keVee)	Analog (V)	Digital (V)
Calibration	478	478	0.32	0.52

2.2. Measured-Data Processing

Matlab scripts were written to process the pulses from both PSD systems. Pulses that went above the maximum pulse height allowed by the V1720 (2 V) were removed from the data sets, and there was no double-pulse cleaning. The total number of accepted pulses (i.e., non-clipped pulses) was 981,639 for both measurements listed in table 4.

Table 4: Data Summary.

PSD System	Detector Gain (V)	Threshold (keVee)	Points per Pulse	Pulse Length (ns)
Analog	-1260	100	376	1504
Digital	-1260	100	100	400

The data for each system was then split into three, 300 keVee bins, starting from 100 keVee and spanning through 1000 keVee. A fourth bin was included that spanned from 100 keVee to 1800 keVee (close to the maximum light output measured by the digital PSD system). This same upper threshold was then applied to the analog PSD data. The voltage values for each bin were calibrated according to table 3 and are reported in table 5.

It should be noted that the measurement threshold of the MPD4 was set according to a fixed discrimination voltage, where pulses greater than 0.07 V in amplitude were accepted. Pulses with these amplitudes do not compare directly in energy to digital-PSD-based pulses of 0.07 V in amplitude. This is because the AMPL amplitude is representative of the fast component integral of the scintillator pulse. Therefore, even though the digital and analog PSD measurement thresholds were equal, the MPD4 in

actuality accepted slightly smaller pulse amplitude than the digital PSD system to account for the integral represented by AMPL.

Table 5: Light-output bins.

Bin Number	Light output range (keVee)	Analog (V)	Digital (V)
1	[100 400]	[0.07 0.27]	[0.11 0.44]
2	[400 700]	[0.27 0.47]	[0.44 0.76]
3	[700 1000]	[0.47 0.61]	[0.76 1.10]
4	[100 1800]	[0.07 1.22]	[0.11 1.97]

3. Results

Two measurements were conducted, each using the same Cf-252 source, the same EJ-309 organic-liquid scintillator, and the same PMT. The analog and digital PSD images are shown in figures 7a and 7b, respectively. PSD images were calculated in Matlab using color contour plots, and the light-output bins were overlaid on each plot according to their respective calibration data (table 5). The bin widths used for the contour image in the x and y directions were kept consistent. Although the contour bin widths are the same between figures 7a and 7b, there appear to be more pulses in figures 7b (digital) than 7a (analog). This is because the TAC and Ratio data have inherently different domains, where TAC ranges from 0 to 2 (for the V1720 case) and Ratio ranges from 0 to 1. The analog and digital PPH images for the first, second, and third bins are shown in figures 8a and 8b, figures 9a and 9b, and figures 10a and 10b, respectively. Figures 11a and 11b show the analog and digital PPH images over the entire light-output range measured (100 to 1800 keVee), for analog and digital PSD, respectively. The FOM (equation 1) for each system was calculated over each range and the resulting values are reported in table 6, and illustrated as a function of light-output bins in figure 12. Table 7 reports the peak separation between gamma ray and neutron distributions in the PPH's, as well as their FWHM values, for each bin.

Table 6: FOM Results.

Bin Number	Analog PSD FOM	Digital PSD FOM	Percent Difference (%)
1	0.73	1.22	50.3
2	1.31	1.47	11.5
3	1.40	1.60	13.3
4	0.94	1.15	20.1

A notable difference between the analog-PSD and digital-PSD systems is the spread in the neutron distribution in all PPH images. Analog PSD appears to have a wider spread in neutron counts at lower light-output values (< 1000 keVee) than digital PSD. Given that the FOM equation strongly depends on the FWHM of both particle distributions, the dramatic spread in neutron data for the analog PSD system likely contributes to its lower FOM result in contrast to digital PSD, especially in the first bin. The gamma-ray distributions in the PPH images on the other hand appear to have the same shape overall. The second and third bins exhibit less difference in performance capabilities. This is expected, given that particle discrimination improves as energy deposition is increased for both systems.

Figure 7a: Analog PSD (pulses digitized by v1720). The bin widths are 0.005 V and 0.0025 V on the x and y axis, respectively, and there are a total of 40 color bins.

Figure 7b: Digital PSD (using v1720). The bin widths are 0.005 V and 0.0025 V on the x and y axis, respectively, and there are a total of 40 color bins.

Figure 8a: Analog PPH (pulses digitized by v1720).
The bin width is 0.01 V and the light-output range for this data is 100 to 400 keVee.

Figure 8b: Digital PPH (using v1720).
The bin width is 0.02 (dimensionless) and the light-output range for this data is 100 to 400 keVee.

Figure 10a: Analog PPH (pulses digitized by v1720).
The bin width is 0.01 V and the light-output range for this data is 700 to 1000 keVee.

Figure 10b: Digital PPH (using v1720).
The bin width is 0.02 (dimensionless) and the light-output range for this data is 700 to 1000 keVee.

Figure 11a: Analog PPH (pulses digitized by v1720).
The bin width is 0.01 V and the light-output range for this data is 100 to 1800 keVee.

Figure 11b: Digital PPH (using v1720).
The bin width is 0.02 (dimensionless) and the light-output range for this data is 100 to 1800 keVee.

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Table 7: PPH Results.

Bin Number	Gamma-neutron Peak Separation (keVee)		Gamma PPH FWHM (keVee)		Neutron PPH FWHM (keVee)	
	Analog	Digital	Analog	Digital	Analog	Digital
1	298.75	167.76	112.03	61.22	296.36	76.57
2	365.97	144.78	88.13	40.17	184.33	58.19
3	325.64	130.53	71.70	32.72	161.32	48.99
4	321.16	153.97	92.61	45.96	249.46	87.24

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4. Discussion

258 Digital PSD demonstrated significantly better performance over the MPD4 analog-PSD system by
259 approximately 50%, within the range from 100 to 400 keVee, and marginally better performance above
260 400 keVee. Over all (100 to 1800 keVee), digital PSD outperformed the MPD4 by approximately 20%.

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262 To further improve digital PSD, the sampling rate should be increased from 250 MHz to better resolve
263 the PSD information carried in the tail of a pulse. Previous work from 2011 has shown that digital-PSD
264 performance was improved by increasing the sampling rate [2,5]. Other work from 2005 supports this
265 result [6], whereby liquid-scintillator pulses created by a Cf-252 particle depositing above 100 keVee
266 were digitized at a sampling rate of 40 MHz, achieving an overall FOM value of 0.89 overall; lower than
267 the overall digital PSD FOM value (1.15) reported in this paper for a sampling rate at 250 MHz. The PSD
268 performance of the MPD4 would not benefit from an increased sampling rate given that the pulse

length was 1 μ s-long. Any further improvement in analog PSD performance would have to come from even finer optimization techniques.

Given the measurement constraints described in this paper, the selection process likely depends on which system could provide better usability for a specific detection application. For example, the MPD4 has a built-in trigger mechanism that automatically opens a gate for accepting pulses when a certain type of particle has been detected. This built-in discrimination trigger provides easy access for the user to set up a particle alarm. While this same feature can be implemented in digital PSD, it is not as user-friendly given that one would need to program this capability to an FPGA. For detection applications that rely on particle discrimination at lower energies (< 100 keV), however, the best system to choose would likely be a digital-PSD system based on a 14-bit, 500-MHz digitizer [5].

5. Conclusion

Analog-PSD (Mesytec MPD4) and digital-PSD (CAEN V1720) systems were compared, to assess their PSD performance. It was found that the digital-PSD system outperformed the analog-PSD system; by approximately 20% overall. Additionally, digital PSD significantly outperformed analog PSD, from 100 to 400 keVee, by approximately 50%. The greater performance offered by the digital PSD approach was likely due to the V1720's sampling rate (250 MHz), which was fast enough to resolve the shape of the tail; a important component to the digital-charge integration approach. Digital-PSD performance is improved when the shape of the pulse is more accurately resolved. While maintaining detector gain and increasing the sampling rate, it is expected that digital PSD can be further improved.

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