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A New Pulse Pileup Rejection Method Based on Position Shift Identification

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Abstract

Pulse pileup events degrade the signal-to-noise ratio (SNR) of nuclear medicine data. When such events occur in multiplexed detectors, they cause spatial misposition, energy spectrum distortion and degraded timing resolution, which leads to image artifacts. Pulse pileup is pronounced in PETbox4, a bench top PET scanner dedicated to high sensitivity and high resolution imaging of mice. In that system, the combination of high absolute sensitivity, long scintillator decay time (BGO) and highly multiplexed electronics lead to a significant fraction of pulse pileup, reached at lower total activity than for comparable instruments. In this manuscript, a new pulse pileup rejection method named position shift rejection (PSR) is introduced. The performance of PSR is compared with a conventional leading edge rejection (LER) method and with no pileup rejection implemented (NoPR). A comprehensive digital pulse library was developed for objective evaluation and optimization of the PSR and LER, in which pulse waveforms were directly recorded from real measurements exactly representing the signals to be processed. Physical measurements including singles event acquisition, peak system sensitivity and NEMA NU-4 image quality phantom were also performed in the PETbox4 system to validate and compare the different pulse pile-up rejection methods. The evaluation of both physical measurements and model pulse trains demonstrated that the new PSR performs more accurate pileup event identification and avoids erroneous rejection of valid events. For the PETbox4 system, this improvement leads to a significant recovery of sensitivity at low count rates, amounting to about 1/4th of the expected true coincidence events, compared to the LER method. Furthermore, with the implementation of PSR, optimal image quality can be achieved near the peak noise equivalent count rate (NECR).

Index Terms—

Detector; GATE; leading edge; library; PET; pileup; position shift; pulse; signal processing

I. Introduction

PULSE pileup is a common problem in multiplexed photon counting scintillator detectors. When these detectors are readout by resistor divider networks, pileup events cause event loss and mis-positioning [1], energy spectrum distortion [2] and degraded timing resolution [3]. In turn, these effects lead to deterioration of image signal-to-noise ratio (SNR), loss of resolution and contrast and the introduction of artifacts.

Significant efforts have been devoted to pileup event correction. The delay-line technique [4]–[7] reduces the probability of signal pileup and improves the count rate capability by clipping the pulse tails to a shorter time. Unfortunately, this approach degrades the energy and spatial resolution performance for all count-rates because of the reduced collection of scintillation light signal. A number of other methods, based on pulse shape discrimination have been proposed to identify pulses involved in pileup events. Examples are: leading edge discrimination, monitoring the incoming signal and detecting pileup events based on the rising edge of the pulse signal [8], [9], methods identifying pileup events by time-over-threshold [6], [10], baseline monitoring [11], pulse peak detection [12] and matched filter [13]. Recognized pileup pulses are commonly rejected to improve recorded data by removing this contamination [4], [14]. Also, several methods have broadened the scope of these techniques by focusing on the information recovery of each single event in a multi-event pileup by pulse-tail extrapolation [2], [8], [15] or pulse waveform reconstruction [9]. These methods have been demonstrated to maintain a much better linear relationship between activity and count rate, and extend the dynamic range of detectors.

PETbox4 is a bench top PET scanner dedicated to high sensitivity and high resolution imaging of mice designed and built at our institute. The detailed specifications of the PETbox4 system, including energy resolution, timing window, etc, are summarized in [16]. The high absolute sensitivity [17] of PETbox4, together with the long decay time of BGO used as the detector material and the highly multiplexed electronics lead to a significant fraction of pileup, reached at lower total activity than for comparable instruments. Therefore, it is important to implement pileup event detection for PETbox4. For conventional scintillator based PET detectors, the signal intensity output is related to the number of scintillation light photons (signal information carrier) detected per unit time. Due to the low light output and long decay time of BGO, the signal intensity of the PETbox4 detector is much lower than systems using higher light output and faster scintillators such as LSO. This results in larger statistical variations in the signal waveforms of the PETbox4 detectors. Because conventional pileup rejection methods identify and reject pileup events by monitoring the shape of individual pulse waveforms, the higher level noise in the PETbox4 detector pulse leads to erroneous event rejection and loss of true event sensitivity.

In this manuscript, a novel pileup rejection method named position shift rejection (PSR) is introduced. In contrast to pulse shape discrimination [8], [10]–[13], the PSR method identifies pileup by detecting position shifts on event location over the course of pulse signal integration. The PSR method presented here is aimed at accurate discrimination of pileup events for rejection, while pileup pulse recovery is out of the scope of this study. The performance of the PSR is compared with the results acquired by conventional pulse leading edge discriminator based pileup rejection (LER), and with no pileup rejection implemented (NoPR).

II. Methods

A. Pileup in PETbox4

The PETbox4 system is comprised by 4 flat panel detectors, arranged in box shape geometry [16]. Each PETbox4 detector panel consists of a 24×50 pixelated BGO scintillator array with individual crystals measuring $1.82 \times 1.82 \times 7$ mm and a pitch of 1.90 mm (Proteus, Chagrin Falls, OH). The BGO array is coupled to two H8500 position-sensitive photomultiplier tubes (PSPMT; Hamamatsu Photonics, Bridgewater, NJ) for scintillation light detection. A charge division resistor network [18] is used to convert the 128 anode outputs from the two PSPMTs into two position encoding signals, denoted as x and y , and the sum of the PSPMT outputs, denoted as sum [19].

The x , y position signals and the sum energy signal are digitized by free running analogue-to-digital converters (ADC) and accumulated in a field programmable gate array (FPGA) with an integration period of 3τ ($0.9 \mu\text{sec}$) for collecting about 95% of the BGO scintillation light, where τ is the decay time constant of the BGO scintillation pulse ($0.3 \mu\text{sec}$). Event positions are calculated as $X = x/sum$ and $Y = y/sum$ by the event position logic. Fig. 1 shows a simplified block diagram of the event positioning scheme in PETbox4 [20].

A typical scintillation pulse (sum output channel) from the PETbox4 detector is shown in Fig. 2(a). When two or more annihilation photons interact within a detector panel in the time-frame of one pulse integration period, pileup events are formed by the superposition of a new pulse on the tail from a preceding pulse, as shown in Fig. 2(b). These two (or more) events will be integrated together to produce inaccurate event energy and position measurements, leading to loss of contrast and image artifacts. In this work, a pulse is defined as a pileup pulse, if the adjacent pulses are separated by less than the $0.9 \mu\text{sec}$ integration period (due to the $0.3 \mu\text{sec}$ decay time constant for BGO).

The PETbox4 system reaches a significant fraction of pileup at lower total activity than that for comparable instruments, mainly due to its high absolute sensitivity, together with the long decay time of BGO and the highly multiplexed detector readout. The Geant4 application for tomographic emission (GATE) Monte Carlo simulation software [21] was used to simulate data acquired with a PETbox4 detector. A point source with isotropic emission of back-to-back 511 keV gamma photons was positioned 2.5 cm from the front surface of the PETbox4 detector, mimicking the emission from the center of the field of view (FOV) of the close geometry PETbox4 system. Only gamma interactions were modeled, and the scintillation light collection was not simulated. All simulations were

acquired with an energy resolution of 18%, which is the average measured energy resolution of the PETbox4 [16]. An energy window of 50–650 keV was applied to the singles processing chain at the stage of initial simulation. The *Root* format output from GATE [22] stores information of particle transportation and interactions on an event-by-event basis, allowing event history to be retrieved. The time stamps for individual events were extracted, and from the assumption that pulses separated by less than $0.9 \mu\text{sec}$ are pileup events, the fractions of pileup events at different activity levels were calculated, as shown in Table I.

B. Pulse Leading Edge Rejection (LER) Method

LER is a conventional pileup rejection method that detects pileup events by continuously taking the derivative of the incoming signal waveform to identify the pulse leading edge. The derivatives of the pulses shown in Fig. 2(a) and (b) are shown in Fig. 3(a) and (b), respectively. In Fig. 3(a), the value of the derivative remains below a preset threshold within the 3τ event processing time ($0.9 \mu\text{sec}$), and this event is identified as a non-pileup event. Due to the leading edge of the second pulse which superimposes on the tail from the preceding pulse as shown in Fig. 2(b), the value of the derivative in Fig. 3(b) exceeds the threshold within the event processing time, thus these events are correctly identified as pileup events.

C. Position Shift Rejection (PSR) Method

Our new pileup rejection method PSR is based on the detection of apparent position shifts on event location as the signal is being integrated by comparing positions obtained with three different integration times. This is also shown in Fig. 4, where I_t corresponds to the position obtained with an integration time of t ns. The three integration time intervals and the corresponding thresholds are selected to optimize the pileup event rejection accuracy and avoid inaccurate rejection of non-pileup events. While the optimization details are not shown in this work, attempts to introduce more than three integration intervals led to no obvious improvement. In contrast, if fewer integration intervals (two or one) were used, the rejection accuracy was compromised. The three corresponding thresholds were determined based on the event position convergence characteristics for different integration time intervals. For a non-pileup event, when comparing positions using 100 ns and 200 ns integration, the position values fluctuate within a certain range due to the lower amount of scintillation light collected. The threshold 1 in Fig. 4 was set higher above the fluctuation range (corresponding to about 3.5 crystal pitch), to avoid inaccurate rejection of non-pileup events. For the second and third comparisons (200 ns versus 600 ns, 400 ns versus 800 ns), due to the higher amount of scintillation light collected, the position converges to a more stable location. So the thresholds 2 and 3 could be set lower (1.25 and 1 crystal pitch) to improve rejection performance. The output logic in Fig. 4 is a general operator, applied to all triggered events for extracting those without pileup. Fig. 5(a) and (b) shows the X position as a function of integration time derived from the pulses shown in Fig. 2(a) and (b). In Fig. 5(a), the X position value converges quickly to a relatively stable value within the 3τ event processing time ($0.9 \mu\text{sec}$), and this event is identified as a non-pileup event. In contrast, an obvious position shift can be observed in Fig. 5(b) due to the event pileup shown in Fig. 2(b). As a result, the difference between the values of I_{200} and I_{600} shown in Fig. 4 exceeds the threshold, and these events are correctly identified as pileup events.

D. Synthetic Pulse Train Evaluation

The PETbox4 system employs a digital signal processing board with sixteen 104 MHz free running analogue-to-digital converters (ADC) of 14 bit sampling depth and a field programmable gate array (FPGA) (VHS-ADC, Nutaq, Quebec City) [16], [19], [20]. This board allows the digitization and storage of the entire pulse waveform with adequate resolution in both time and amplitude, and the computation of pulse parameters in real time. The LER and PSR pileup rejection methods described in Section II-B and C can be easily implemented in the FPGA.

To achieve more efficient and systematic signal processing algorithm evaluation, a collection of detector pulses from a database (usually called a digital pulse library) is required to serve as a reference data set, for which the ground truth values regarding event energy, position and timing can be known. With such a reference library, various signal processing algorithms can be tested [23]. Complicated analytical methods together with the information obtained from Monte Carlo simulations can generate simulated pulses by modeling the propagation of scintillation photons, noise and the data acquisition chain [24]–[27]. However, differences between modeling and real conditions will inevitably introduce inaccuracies that can influence evaluations and bias optimization results.

In our previous work, a comprehensive pulse library was acquired by directly recording raw pulses from physical measurements using the PETbox4 detectors and signal processing electronics [23]. This way, the pulse waveforms in the pulse library were sampled with exactly the same signal processing chain as the signals to be processed in real acquisitions in the FPGA. As a result, the use of these recorded pulses for offline evaluation of signal processing algorithms should lead to equivalent results as those yielded from real-time, online FPGA processing. The proposed evaluation method has been consistent with the physical measurements and significantly reduces the time and effort invested [23] for reliable results.

In this study, the digital pulse library was developed for objective evaluation and optimization of the proposed PSR methods. The raw pulse library should be composed by a series of single pulses without pileup. As shown in Table I, singles measured with a $0.37 \mu\text{Ci}$ point source only include 0.35% pileup events. Therefore, a $13.9 \text{ kBq}(0.377 \mu\text{Ci})^{68}\text{Ge}$ point-like source (Eckert & Ziegler Isotope Products, Valencia, CA) was used to acquire the raw data for establishing the pulse library. The pulse library used in this work contained 62500 events, with 3 measurements per event including the x , y position encoding signals and the *sum* signal output from a PETbox4 detector multiplexed by a resistor divider network. The sample size of the pulse library can be easily enlarged.

The effectiveness of the LER and PSR methods was evaluated and compared with the help of the pulse library. One thousand single events including the *sum*, x and y signals were randomly selected from the pulse library and placed into a synthetic pulse train based on timestamps and energy obtained from the GATE simulation, as shown in Fig. 6. The simulation was performed with the National Electrical Manufacturers Association (NEMA) NU-4 scatter fraction phantom (mouse size) [17] filled with $50 \mu\text{Ci}$ of F^{18} . The synthetic pulse train was fed into the signal processing algorithms in MATLAB and an energy window

of 150–650 keV was applied. The positions of detected events were extracted and compared with the known position information from the pulse library as the ground truth reference. The average area for one crystal in the flood histogram was the tolerance criterion for the identification of a shift from the detected position. The evaluation was repeated four times, and the average detected counts with standard deviations calculated from the repeat experiments were reported.

E. Measurement Verification

A) Flood Image and Energy Spectra: To validate the synthetic pulse train results, physical measurements were performed with the PETbox4 system. Flood images for one detector panel were acquired with a cylindrical source (36 mm diameter and 100 mm long) filled with 50 μCi of ^{18}F measured with a dose calibrator (Atomlab 300; Biodex Medical Systems, Shirley, NY) and placed at the center of the FOV. Pileup events identified by the LER and PSR methods were labeled and included in the list mode files. Flood histograms for the entire detector, as well as energy spectra from selected crystals consisting of identified pileup events and non-pileup events were extracted for comparison.

B) System Peak Sensitivity: To evaluate the potential sensitivity loss caused by either the LER or the PSR methods, the system peak absolute sensitivity of the PETbox4 was measured with NoPR, LER or PSR applied. Pileup events identified by LER and PSR were rejected. A ^{68}Ge point-like source (Eckert & Ziegler Isotope Products, Valencia, CA) was placed at the center of the FOV. The activity of the point source was 13.9 kBq (0.377 μCi) measured in a calibrated well-type gamma counter (Wallac Wizard 1480, Perkin Elmer, Shelton, CT). The activity was low enough so that the fraction of the pileup events could be ignored (less than one percent). An energy window of 150–650 keV was applied. Delayed coincidences were subtracted from prompt events before the true coincidences were divided by the actual source activity. This ratio was corrected for the branching ratio of ^{68}Ga (0.89). The peak absolute sensitivity measurements were compared to simulated values obtained from GATE simulations with the same configurations.

C) NEMA NU-4 Image Quality Phantom: To evaluate the effects of pileup rejection on reconstructed image quality, studies were performed using the NEMA NU-4 image quality phantom (Data Spectrum Corporation, Hillsborough, NC) filled with 50 μCi of ^{18}F , measured with a dose calibrator (Atomlab 300; Biodex Medical Systems, Shirley, NY). NoPR, LER and PSR methods were applied. The pileup events identified by LER and PSR were rejected. For each method, two scans were acquired, with the starting activities of 50 μCi and 4 μCi . The acquisition time was 20 minutes each. An energy window of 150–650 keV was applied. Random event corrections were applied by subtracting the delayed coincidences from the prompt events. Dependent on the method and activity used to calculate and correct for the detector efficiencies and system geometry, normalization also affects image artifacts that are caused by pileup events. Therefore, to focus on evaluating the image effects exclusively from the NoPR, LER and PSR methods, no normalization was applied. Finally, to demonstrate the imaging performance that can be achieved with the PETbox4 at both high and low activity levels when the PSR method is applied, count rate dependent normalizations, which were estimated from measurements of a cylindrical source

filled with ^{18}F at 50 μCi and 4 μCi , were applied to the data acquired with PSR. The images were reconstructed by the ML-EM algorithm [28]. A 22.5-mm-diameter and 10-mm-high cylindrical volume of interest (VOI) was drawn over the center of the uniform region of the image-quality phantom. The average concentration values in this VOI and standard deviation (SD) were measured to estimate noise performance and evaluate the image artifacts caused by pileup events.

III. Results

A. Synthetic Pulse Train Evaluation

Table II shows the synthetic pulse train evaluation results applied with NoPR, LER or PSR methods, for the 50 μCi source of ^{18}F . With NoPR, 27% of the total detected events (128 in 473) include pileup that caused mispositioning. When using LER, the mispositioned events due to pileup decreased to 6.7% of the total detected events (21 in 313). These wrong detections were mainly contributed from pileup events consisting of a lower energy event superimposing on the tail of a previous higher energy event, in which the pulse rising edge of the lower energy event was not obvious enough to identify. Besides, it is also difficult for LER to identify the pileup events in which the time stamps of the two pulses are very close (< 100 ns). As a tradeoff, the number of correct detections also decreased by 15% compared to that with NoPR (292 versus 345). This sensitivity loss is mainly due to inaccurate identification of statistical noise fluctuations along the tails of single event scintillation pulses as the leading edge of a pileup event. These large fluctuations result from the variations of the scintillation light signal due to the low light output and long decay time of BGO.

When using PSR, the fraction of mispositioned events due to event pileup decreased to 3.7% of the total detected events (13 in 350). These wrong detections were mainly contributed from the pileup events in which the time stamps of the two pulses are less than 100 ns. The number of correct detections remained close to that with NoPR (337 versus 345). Compared to LER, the new PSR yielded a more effective suppression of mispositioned events, with a small compromise in the fraction of correct detections.

B. Measurement Verification

A) Flood Image and Energy Spectra: Figs. 7–9 show the measured flood images and selected crystal energy spectra acquired by NoPR, LER and PSR.

Fig. 7 shows the results with NoPR applied. The count rate of the detected events shown in Fig. 7(a) was 266 kcps. A cluster of blurred events merges towards the central area of the flood image as shown in Fig. 7(a). This blurred background underneath the events originating in single crystals corresponds to events mispositioned by pileup. In addition, in the crystal energy spectra at the central area of the flood image Fig. 7(b), we observe a pedestal caused by pileup that includes a large fraction of counts with energy higher than the photopeak. Such events correspond to the energy deposited from pileup events and therefore from multiple gamma interactions. These results demonstrate experimentally that a large fraction of the events collected at this activity level (50 μCi) is pileup.

Fig. 8 shows the results with LER applied. Figs. 8(a) and (b) show the measured flood image from one detector panel and the energy spectra from a single crystal, when including only the rejected events. The majority of the rejected events appear as a cluster of blurred events merging towards the central area of the flood image (Fig. 8(a)), corresponding to the mispositioned events caused by event pileup. In addition, a distinct pattern of events resolved by crystals is also obtained in Fig. 8(a), and a small photopeak is observed in Fig. 8(b). These events are non-pileup events that are erroneously rejected by the LER. Fig. 8(c) and (d) shows the measured flood image and selected crystal energy spectra excluding the rejected events using LER. The count rate of the detected events shown in Fig. 8(c) is 177 kcps, and the count rate of the rejected events shown in Fig. 8(a) is 70 kcps. No obvious effect caused by pileup events is observed.

Fig. 9 shows the results with PSR applied. In the flood image including only the pileup events identified by PSR (Fig. 9(a)), a blurred cluster towards the central area of the flood image can be observed with no crystals resolved. No photopeak is obtained in the crystal energy spectra including only rejected events in Fig. 9(b). Fig. 9(c) and (d) shows the measured flood image and selected crystal energy spectra excluding the rejected events using PSR. The count rate of the detected events shown in Fig. 9(c) is 193 kcps, and the count rate of the rejected events shown in Fig. 9(a) is 53 kcps. This result demonstrates that PSR performs more accurate rejection and avoids erroneous rejection and loss of sensitivity compared to LER in singles detection mode.

B) System Peak Sensitivity: Table III summarizes the system peak sensitivity measured using NoPR, LER and PSR methods, as well as the sensitivity estimated from the GATE simulation. The NoPR result agrees well with the GATE result, validating the simulation model. The activity of the measured point source was low enough, and the averaged singles rate of detected events per detector are 2.7 kcps, 2.2 kcps and 2.6 kcps for NoPR, LER and PSR methods. Therefore, the fraction of the pileup events can be ignored and any large decrease in sensitivity at this activity level results from the erroneous rejection of non-pileup events. Compared to about 26% coincidence sensitivity loss when the LER is applied, the sensitivity measured using PSR is in close agreement with that estimated from the GATE simulation, indicating almost no loss of sensitivity in coincidence detection mode when PSR is used.

C) NEMA NU-4 Image Quality Phantom: Fig. 10 illustrates the NEMA NU-4 image quality phantom measurements acquired at 50 μ Ci using NoPR, LER and PSR. The average singles rate of detected events per detector panel are 275 kcps, 173 kcps and 191 kcps for NoPR, LER and PSR methods. Obvious artifacts and spatial distortion can be observed in the NoPR images (Fig. 10(a)): The top left image of Fig. 10(a) shows that the transverse image slice of the uniform region of the image quality phantom has multiple “X” shaped artifacts. In addition, the transverse image slice of the five rod region of the image quality phantom is been distorted. The rods appear as oval shaped towards the center of the field of view, as shown in the top right image of Fig. 10(a). For LER (Fig. 10(b)) and PSR (Fig. 10(c)), the artifacts and spatial distortion are significantly reduced. The uniformity improves from 15.3% (NoPR) to 10.9% (LER) and 10.2% (PSR), respectively. This result is consistent

with the synthetic pulse train simulation results shown in Table II and the measured flood image results shown in Fig. 7–9, demonstrating that both LER and PSR can effectively suppress pileup caused mispositioned events.

Fig. 11(a)–(c) illustrates the NEMA NU-4 image quality phantom measurements acquired at 4 μCi using NoPR, LER and PSR. The average singles rate of detected events per detector are 31 kcps, 26 kcps and 30 kcps for NoPR, LER and PSR methods. At this lower activity level, the images shown in Fig. 11(a)–(c) do not have the pileup caused image artifacts and distortion visible in Fig. 10. The remnant X shaped artifacts in Fig. 11(a)–(c) are due to the box-shaped geometry of the PETbox4 system which leads to gaps between detector blocks and incomplete sampling along the diagonals, and the lack of detector efficiency and geometry normalization. The Fig. 11(b) shows more pronounced artifacts than Fig. 11(a) and (c), which might be due to the inaccurate rejection of non-pileup events by the LER method. For NoPR (Fig. 11(a)) and PSR (Fig. 11(c)), similar number of prompt counts (22 Million (M) for NoPR and 21 M for PSR) are obtained and similar uniformity (12.2% for NoPR and 12.1% for PSR) is measured. For the LER method (Fig. 11(b)), the uniformity deteriorates to 15.2% in part due to the 23% prompt counts loss (17 M for LER versus 22 M for NoPR). In comparison, an image quality phantom image acquired at 50 μCi using PSR is shown in Fig. 11(d). The measurement was taken for 4.6 minutes and the same prompt counts (22 M) as that in Fig. 11(a) were acquired. No obvious difference on uniformity is measured from Fig. 11(a), (c) and (d). These results are consistent with the synthetic pulse train simulation results shown in Table II and the system peak sensitivity results shown in Table III, indicating that LER trades off against sensitivity loss, while PSR performs more accurate rejection and avoids erroneous rejection and loss of sensitivity compared to LER.

Fig. 12 illustrates the NEMA NU-4 image quality phantom measurements acquired at 50 μCi (Fig. 12(a)) and 4 μCi (Fig. 12(b)) using PSR and with the activity dependent normalizations applied. The uniformity further improves to 7% (50 μCi) and 11% (4 μCi), and the artifacts and spatial distortion are effectively suppressed. The phantom activity at the noise equivalent count rate (NECR) curve peak is around 40 μCi as reported in the PETbox4 count rate performance measurement in [16]. The NECR curve peak of the PETbox4 is reached primarily due to detector saturation caused by pileup events. The result shown in Fig. 12(a) demonstrates that with appropriate pileup rejection and normalization applied, optimal imaging performance can be achieved near the NECR peak activity.

IV. Discussion and Conclusions

In this work, PSR, a novel pileup rejection method, is introduced and compared with the conventional LER method.

Conventional LER identifies pileup events based on the shape of the individual pulse waveform. As shown in Fig. 2, the scintillation pulse output from the PETbox4 detector shows large statistical variations due to the low light output and long decay time of BGO. As a result, identification of pileup events superimposed on the tails of preceding events is challenging and therefore a fraction of pileup events is not effectively identified. At the same time, statistical variations in the pulse of a non-pileup event might be inaccurately identified

as the leading edge of a pileup event, leading to erroneous rejection of good events and loss of sensitivity.

Both simulated and measured results in this work demonstrate that PSR achieves high accuracy in pileup rejection, maintaining no significant compromise in sensitivity at low activity levels. The better performance of PSR is primarily due to its identification scheme that takes into account the correlation of all the position encoding and energy pulses readout from a multiplexed detector. The PETbox4 detector uses a resistor divider network circuit to multiplex 128 PMT anode outputs into sum, x and y signals [18]. Dark counts from PMT anodes and the noise from the resistor network can be ignored in the detected signal, so the noise in the detected pulse waveform is mainly due to scintillation photon detection statistics. These variations are independent on whether the signal is in x , y or sum form. As a result, when a gamma photon interacts with a PETbox4 detector, the output x and y pulses appear as their corresponding sum pulse scaled by factors that are proportional to the coordinates of that interaction point. In other words, the shapes of the x , y and sum signal waveforms are similar, with the difference mainly on signal amplitudes. Due to the similar (correlated) statistical variations in the x , y position encoding signals and the sum signal, the effects of the pulse noise on calculated position values are cancelled out through the division, and the calculated positions for a non-pileup event converge rapidly and remain stable during the integration time, as shown in Fig. 5(a). This indicates that the noise in the pulse shape is less likely to lead to variation of the calculated position value. As a result, erroneous rejection of non-pileup events and sensitivity loss can be suppressed. If a pileup event happens with two gamma photons detected at different locations of the detector within the integration time, the x and y position signals will be contributed in part by each of the two distinct interactions. This will break the correlation between the pulse shapes of the x , y position encoding signals and the sum signal. As a result, a clear shift in calculated event position as a function of integration time will be obtained indicating event pileup, as shown in Fig. 5(b). In contrast to the conventional methods which rely on individual pulse shape, the PSR method takes advantage of the correlation of all the output pulses. This makes it more useful for scintillators with low light output and long decay time such as BGO, which yields signal waveforms with large variation.

The identification of event pileup acts as the first step of various pileup event recovery methods [2], [8], [9]. It might be possible to incorporate the proposed position shift based pileup identification scheme with other existing pileup recovery methods to further decrease the count rate loss and extend the dynamic range of imaging systems. On the other hand, pileup event recovery is challenging as it will inevitably introduce additional noise on recovered events, potentially leading to degradation on spatial and energy resolution and loss of image contrast. Pileup event recovery is currently under investigation.

A limitation of PSR is that it is not applicable to counting (non-imaging) systems such as nuclear spectrometers or PET detectors with individual crystal readout, in which only one signal is derived from individual detection. Another limitation is that it is more difficult for PSR to identify pileup events in which the time stamps of the two pulses are very close (< 100 ns). As shown in Fig. 5(a), for a non-pileup event, the position value is “shifting” during the first 100 ns integration time, in order to converge to detected position value. As

a result, position shifts during the first 100 ns integration time cannot indicate event pileup. This limitation though is not unique for PSR. As two events in a pileup become very close, the resulting pileup pulse will appear as a single non-pileup pulse, which is also difficult to identify by pulse shape discrimination methods such as LER.

PSR has been successfully implemented in the prototype PETbox4 system. The application of PSR is not restricted to PET scanners. It is applicable to cameras that use multiple correlated signals to decode the location of interaction, such as conventional SPECT detectors and gamma cameras. PSR can be implemented by employing integrators, comparators and registers, which can be easily achieved in most digital and analog systems without adding much to the complexity, hardware and production cost. In conclusion, the proposed PSR method is a feasible technique of addressing the problems of pulse pileup in imaging scintillator detectors.

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Fig. 1.
Block diagram of the PETbox4 event positioning algorithm.

Fig. 2. Signal waveform (sum): (a) a typical scintillation pulse; (b) a typical pileup event.

Fig. 3.

(a) Derivative of the scintillation pulse shown in Fig. 2(a); (b) Derivative of the pileup pulses shown in Fig. 2(b).

Fig. 4.
Position shift identification based pileup rejection scheme.

Fig. 5.

X position in arbitrary units obtained with different integration time: (a) a typical scintillation pulse; (b) a typical pileup pulse.

Fig. 6.
Synthetic pulse train evaluation flow chart.

Fig. 7.

Data acquired by NoPR: (a) flood image; (b) selected crystal energy spectra. The location of the selected crystal is indicated by the arrow in the corresponding flood image.

Fig. 8.

Data acquired by LER: (a) flood image and (b) selected crystal energy spectra including only rejected events; (c) flood image and (d) selected crystal energy spectra including only detected events. The location of the selected crystal is indicated by the arrow in the corresponding flood image.

Fig. 9.

Data acquired by PSR: (a) flood image and (b) crystal energy spectra including only rejected events; (c) flood image and (d) crystal energy spectra including only detected events. The location of the selected crystal is indicated by the arrow in the corresponding flood image.

Fig. 10. Image quality phantom images acquired at 50 μCi by (a) NoPR, (b) LER and (c) PSR.

Fig. 11.

Image quality phantom images acquired at 4 μ Ci for 20 minutes by (a) NoPR, (b) LER, (c) PSR, and at 50 μ Ci for 4.6 minutes by (d) PSR.

Fig. 12.

Image quality phantom images acquired by PSR at (a) 50 μ Ci and (b) 4 μ Ci. Activity dependent normalizations were applied respectively.

TABLE I

Fractions of Pileup Events at Different Activity Levels

Activity	0.37 μ Ci	10 μ Ci	30 μ Ci	50 μ Ci
% of Pileup	0.35	12.6	33.4	49.3
Counts / sec	2.8k	75.4k	226k	377k

TABLE II

Pulse Train Evaluation Using Different Methods

Methods	NoPR	LER	PSR
No. of Wrong	128 $\pm$ 11	21 $\pm$ 3	13 $\pm$ 3
No. of Correct	345 $\pm$ 5	292 $\pm$ 7	337 $\pm$ 11

TABLE III

System Peak Sensitivity Using Different Methods

Methods	NoPR	LER	PSR	GATE
Sensitivity (%)	17.9	13.1	17.3	17.7

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