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REAL-TIME IMPLEMENTATION OF A DECONVOLUTION FILTER FOR GAMMA RAY SPECTROSCOPY

Mohamed Deriche, Muhammad Raad*

Electrical Engineering Department
**Computer Engineering Department*
King Fahd University Petroleum and Minerals, Dhahran 31261, Saudi Arabia
e-mail: mderiche@kfupm.edu.sa
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In this paper, we propose a new approach for Real-Time detection of pileup in Gamma-ray spectroscopy using finite length deconvolution filters; in particular, a 3-point deconvolution with Savitzky Golay pre-filter is discussed. The approach was tested and proven to be able to resolve accurately pileup in 93% of the cases. Using the proposed approach, the number of pileup events can be reduced by eight folds. The setup was tested with both simulated data and random signals from a ^{137}Cs test source. More specifically, Gamma pulses, from a 2 inch NaI(Tl) scintillation detector, were captured as single and double pulses for the purpose of testing the proposed peak detection algorithm. The algorithms developed here were then implemented in real time using a high performance floating-point processor, the TMS320C6711. A number of optimisation levels were achieved using the Code Composer Studio profiler based on critical timing to satisfy the real-time constraints of Gamma-ray spectroscopy systems. A comparison in complexity and real time computations among various deconvolution algorithms has been carried using the TMS320C6711 processor.

1. INTRODUCTION

A common problem in nuclear spectroscopy is pulse pileup caused by the non-zero response time of detection systems. For Germanium detectors, the time required to collect the complete ionisation current, associated with an event, ranges from 0.5 to 6.0 μs [1]. The fact that pulses from a radiation detector are randomly spaced in time can lead to interfering effects between pulses at high counting rates. These effects are generally called pileup, and can be minimised by making the total width of the pulses as small as possible [2].

Pileup normally leads to degradation in energy resolution at the input of the detector. Pileup phenomena can be of two types: The first type is known as tail pileup and involves the superposition of pulses over the long duration tail from a preceding pulse (Fig. 1). Tails can persist for relatively long periods of time, so that tail pileup can be significant even at relatively low counting rates. A second type of pileup is peak pileup, which occurs when the mutual pulse spacing between two overlapping pulses is less than T_p, where T_p is the peaking time [2] (Fig. 2).

Traditionally, researchers had a tendency of rejecting all types of pileup when these are detected [3]. Instead of rejecting all types of pileup, we propose here to process tail pileup, and reject peak pileup, which occurs less frequently in nuclear spectrometry [3].

The objective of our study is to develop robust peak detection algorithms to resolve tail pileup in Gamma-ray events, and implement such algorithms in real time using the DSP (digital signal processing) TI (Texas Instruments) platform. In this work, we propose to use deconvolution techniques to reduce (or prevent) pileup in nuclear spectrometry. The condition of occurrence of pileup in intervals comparable to the pulse-shape length has also been quoted by a number of researchers [4]. For our experiments, Gamma-ray records captured at the Energy Research Lab (ERL), KFUPM, were digitized at a sampling rate of 50 MHz resulting in a sampling resolution of 20 ns. Our main objective was to detect pileup then process it to reduce its effects.

Before discussing the proposed deconvolution algorithm to reduce the effect of tail pileup, we will briefly discuss peak pileup and its consequences. Peak pileup occurs when two pulses superimpose such that the distance between these is less than the pulse rise time (10–90% of peak amplitude). Its effect is measured by estimating the effective width between the two pulses. It is difficult to define the effective pulse width,

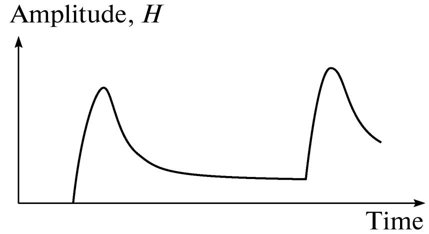

Fig. 1. Pileup effect on a pulse peak from the tail of a preceding pulse.

but it can be approximated by the FWHM (Full Width Half Maximum) of the signal. A typical FWHM of a real Gamma-ray pulse recorded at the ERL is 2.88 μs, and assuming pulses occurrence follows a Poisson distribution with an arrival rate of 280000 event/s, we can easily show that the probability of possible overlap of events within the FWHM time interval is equal to 0.56 or 56%.

Note that we opted for a more comprehensive probabilistic model to control the arrival rate hence making the modelling process more realistic. It is well known that in tail pile-up, the amplitude of the first pulse is not distorted while the amplitude of the second is. However, when the pulse separation is less than the peak time T_p, complete overlap can occur in which the two pulses appear as one distorted pulse of twice the original amplitude, which is then categorized as peak pile-up. To reduce the effect of pileup, researchers have considered a number of techniques. One particular technique that we discuss here is deconvolution [2, 5–7].

2. PEAK DETECTION USING DECONVOLUTION

One common problem in nuclear spectrometry applications is that of determining the input to a shaping amplifier when the output is known. We know that the shaping system has some effects on the input pulse expressed in terms of the impulse response of the system. To handle this problem, we design an inverse system, and cascade it with the original one. The output of this system approximates the input with respect to a certain measure. Furthermore, since the shaping system gives an output $y(n)$ that is the convolution of the input $x(n)$, with the impulse response $h(n)$, the inverse system takes $y(n)$ and produces $x(n)$. This operation is what we know as deconvolution operation [8].

A number of researchers have used deconvolution techniques to reconstruct the initial detector impulse signal from the shaped CR-RC amplifier output pulse [4]. The CR-RC system is described by its impulse response given as $\left(\frac{t}{\tau}\right)e^{\frac{-t}{\tau}}u(t)$ where τ is the time constant of the impulse response [2].

Gadomski and Hall, in [9], showed that only three non-zero weights are necessary to represent the deconvolution filter:

$$s_k = w_1 v_k + w_2 v_{k-1} + w_3 v_{k-2}. \tag{1}$$

Where s_k is the k^{th} sample of the input, w_1, w_2, w_3 are the filter weights, and v_k is the output sequence. The values of the weights are given by:

$$w_1 = \frac{1}{X}e^{X-1}; \tag{2}$$

$$w_2 = \frac{-2}{X}e^{-1}; \tag{3}$$

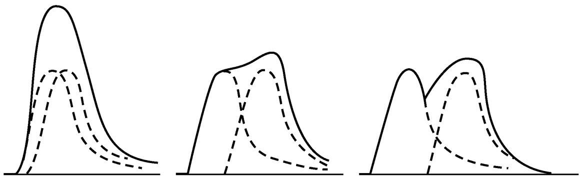

Fig. 2. Effect of varying degrees of overlap on the Gamma-ray pile-up.

$$w_3 = \frac{1}{X}e^{-X-1}. \tag{4}$$

Here $X = \Delta t/\tau$, and Δt is the sampling period [9].

It is easy to show that the cascading of two successive 3-point deconvolution filters, results in a four-point deconvolution filter as shown below [5]:

$$s_k = w_1 v_k + w_2 v_{k-1} + w_3 v_{k-2}; \tag{5}$$

$$s_{k+1} = w_1 v_{k+1} + w_2 v_k + w_3 v_{k-1}. \tag{6}$$

This leads to:

$$s_k = w_1 v_{k+1} + (w_1 + w_2) v_k + (w_2 + w_3) v_{k-1} + w_3 v_{k-2} \tag{7}$$

(4-point filter).

Using a similar procedure to the above, a combination of three successive 3-point deconvolution filters, can be easily shown to lead to a 5-point deconvolution system:

$$s_k = w_1 v_{k+2} + (2w_1 + w_2) v_{k+1} + (w_1 + 2w_2 + w_3) v_k + (w_2 + 2w_3) v_{k-1} + w_3 v_{k-2}. \tag{8}$$

Deconvolution has its effect on series and parallel noise. The series noise generator represents the thermal noise of the majority charge carriers in the channel of the first field effect transistor (FET) in the preamplifier. The parallel noise arises as a thermal noise in resistances connected to the preamplifier input and as a detector leakage current shot noise. It has been proved in Hall's work [10] that deconvolution increases the series noise for all values of X, while it decreases the parallel noise. Note that deconvolution provides a way to remove pulse broadening which was deliberately introduced by the preamplifier. In order to analyze the effect of noise introduced as a result of deconvolution, we compared the performance of 3-point, 4-point and 5-point deconvolution algorithms with their performance after adding a pre-filtering stage. Two well-known filters used in spectroscopic applications have been considered: the moving average (MA) filter and the Savitzky Golay filter (also known as moment preserving filter).

The MA filter achieves significant noise reduction at the expense of signal distortion. To reduce this distortion while retaining noise attenuation, simple polynomials can be fitted to the data. Savitzky and Golay filters involve fitting a polynomial to a set of noisy observations within a certain window. We have used the error

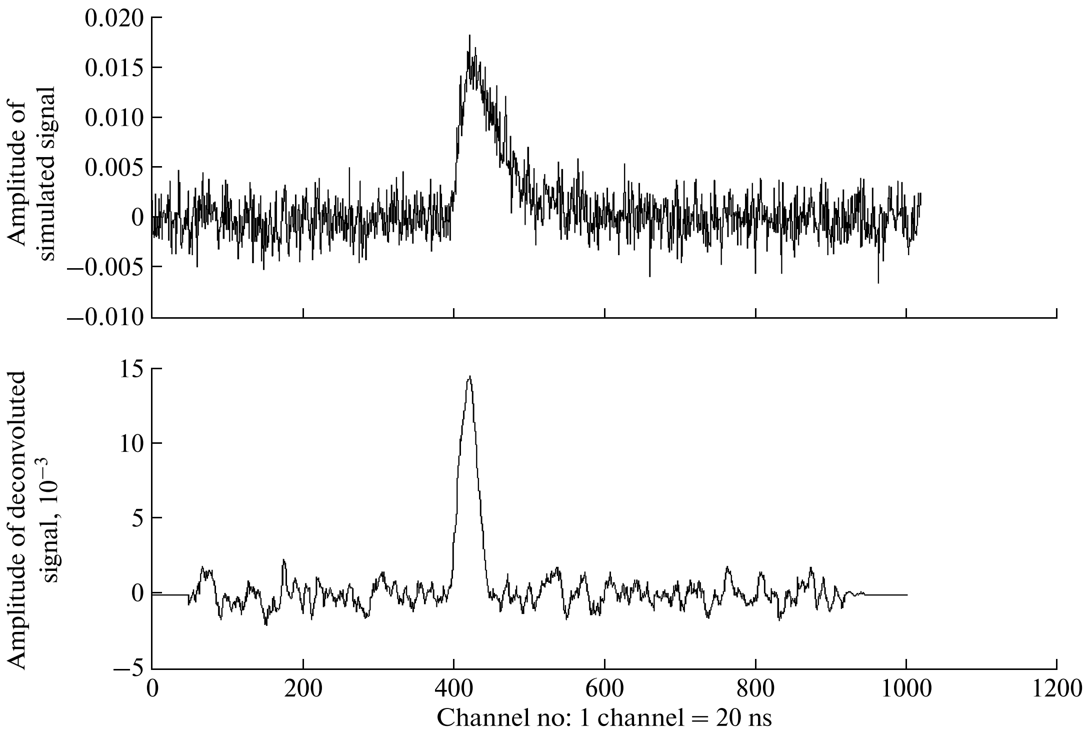

Fig. 3. Result of 3-point deconvolution in the presence of a 9-point moving average prefilter stage.

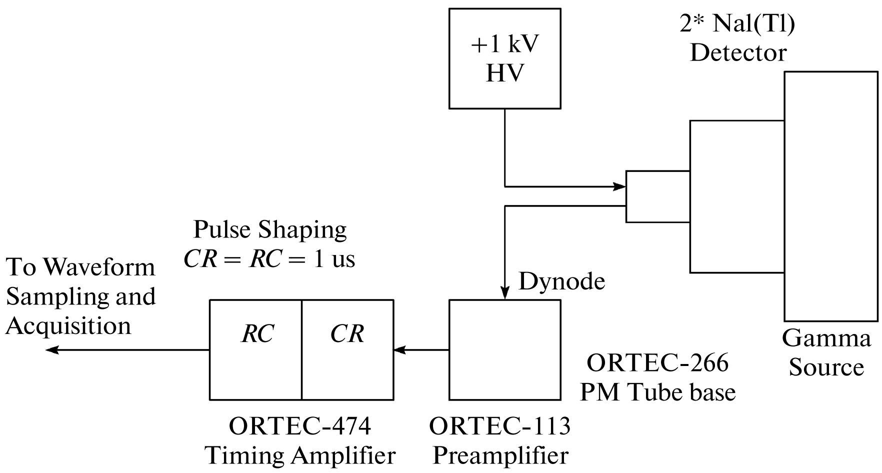

Fig. 4. Experimental setup for Gamma-ray spectroscopy.

criterion for determining whether a certain peak detection algorithm performs well for a certain amount of noise (a percentage error less than 1%). Figure 3 shows the result of applying the 3-point deconvolution on simulated Gamma-ray events corrupted with white Gaussian noise after we included the prefilter stage. We observe the improved amplitude resolution due to enhancement in the signal.

In our experiments, the set-up was also tested with random signals from a ^{137}Cs test source. Gamma pulses from a 2 inches NaI(Tl) scintillation detector were captured as single and double pulses for the purpose of testing the proposed peak detection algorithms (Fig. 4). The percentage of peak pileup from the Gamma-ray records has been estimated to be around 15%. The initial percentage of pileup measured from the Gamma pulse content, was estimated to be 56%. The 3-point deconvolution algorithm applied to tail pileup events, digitised at the ERL Lab (KFUPM), was tested by running it on a number of Gamma-ray records, which

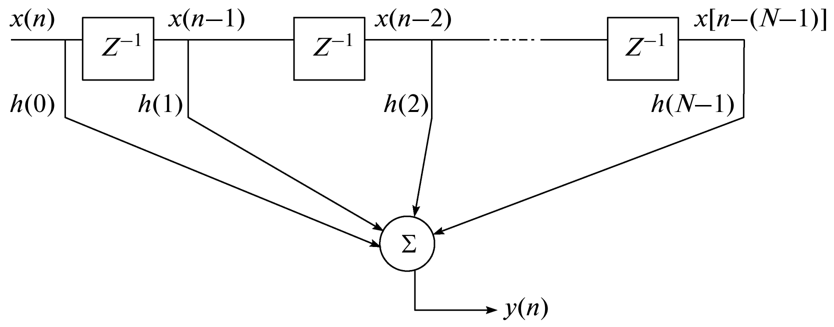

Fig. 5. A typical structure of an FIR deconvolution filter.

consisted of peak pileup, tail pileup, and separate Gamma pulses. The 3-point deconvolution succeeded in resolving pileup by achieving a performance of approximately 93% pileup free events, or 7% remaining tail pileup (7% of Gamma events corrupted with pileups were not resolved by the 3-point deconvolution). In other words, pileup was reduced by eight folds (from 56% down to 7%).

3. REAL TIME IMPLEMENTATION OF GAMMA-RAY ALGORITHMS

The recent advances in DSP technology have led to the development of powerful floating point DSP processors using parallel processing. The exceptionally high performance exhibited by these processors motivated us to test our algorithms in a real-time environment. We chose the TMS320C6711 development board that is commonly used in educational environments. We implemented our algorithms using SIMULINK, then compiled these using the code-composer studio [11].

The 3-point, 4-point and 5-point deconvolution algorithms were implemented using the direct structure of Finite Impulse Response (FIR) filters. The operation shown in Fig. 5 requires N multiply-accumulates (MACs) operations. The TMS320C6711 DSP processor can perform up to 300 Million MACs/sec, resulting in approximately 2 MACs/cycle. This implies that the C6711 can perform the 3-point deconvolution in $N/2$ CPU cycles, where N is number of filter coefficients. Since the Gamma record pulse tail extends up to approximately 520 samples, and based on a speed of 300 Million MACs/s, we can easily show that the computation time taken by the 3-point deconvolution plus the 27 point Savitzky Golay filter is about 52 μs for the complete record.

Figure 6 shows that the 3-point deconvolution filter gives the best pileup suppression (a residual pile up of only 7%) for $X = 2/5$ and $X = 1/2$. However, the 4-point deconvolution filter gives the same pileup suppression, but for a lower value of X ($X = 1/5$). This result is expected because in order to counter effect the loss in resolution caused by the 4-point deconvolution, one has to sample with a lower sampling period, hence a lower X (Fig. 6). Although the 4-point deconvolution filter resulted in 11% residual for $X = 1/2$, it gives a Signal-to-Noise Ratio (SNR) of almost 37 dB, or in other words, an enhancement of almost 7 dB compared to the 3-point deconvolution for the same value of X as shown in Fig. 7. See also Fig. 8a, 8b, 8c and 8d for the effect of applying the 3-point, 4-point and 5-point deconvolution algorithms on real Gamma-ray pile-up for $X = 1/2$, after preprocessing it using

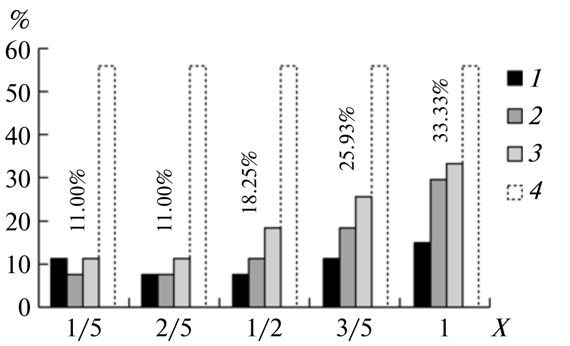

Fig. 6. Comparison of pileup suppression for various deconvolution algorithms: (*1*) pileup for 3 pts deconvolution; (*2*) pileup for 4 pts deconvolution; (*3*) pileup for 5 pts deconvolution; (*4*) pileup before applying deconvolution algorithms.

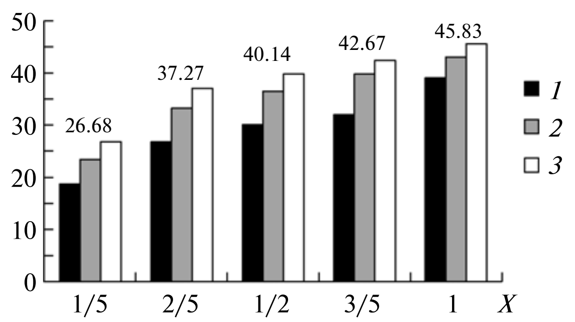

Fig. 7. Comparison of SNR (dB) for 3 pts (*1*), 4 pts (*2*), 5 pts (*3*) deconvolution algorithms.

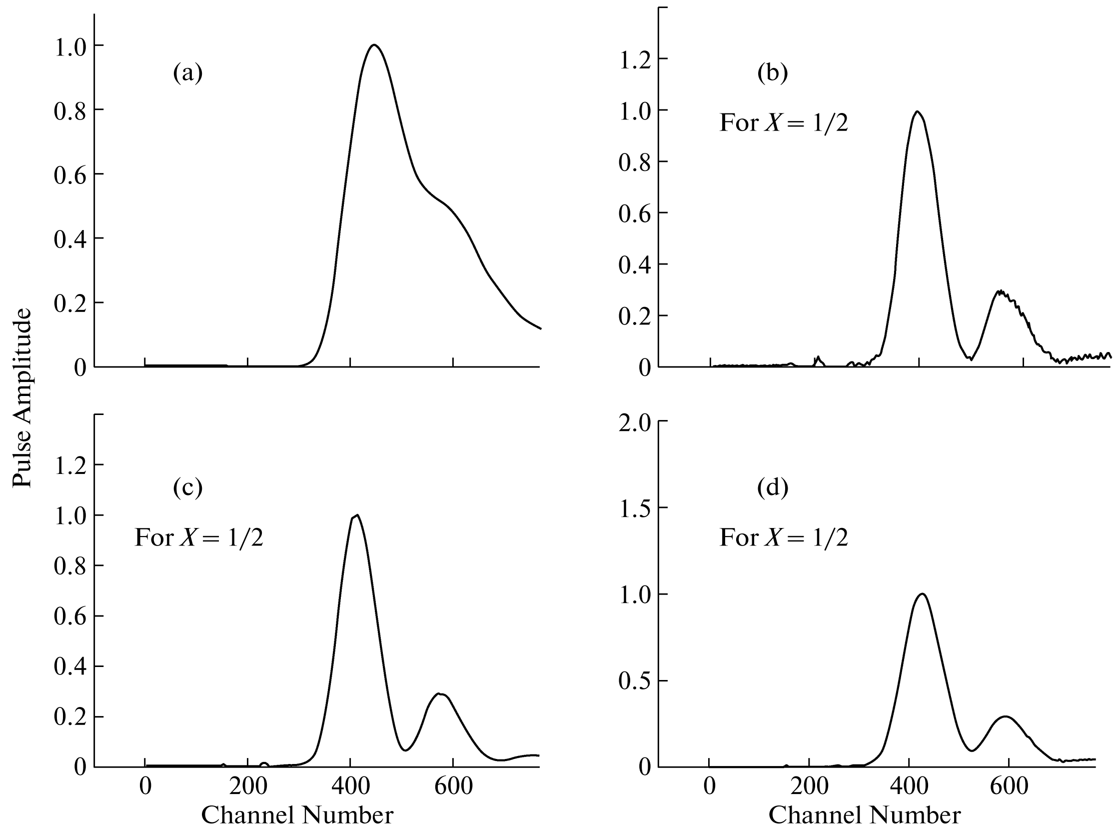

Fig. 8. (a) An example of a Gamma-ray pileup record; (b) 3-point deconvolution result for $X = 1/2$, SNR = 30 dB; (c) 4-point deconvolution result for $X = 1/2$, SNR = 37.41 dB; (d) 5-point deconvolution result for $X = 1/2$, SNR = 43.18 dB.

a Savitzky Golay prefilter. It is also observed here that the 5-point deconvolution algorithm does not perform well in recovering pile-up compared to 3-point and 4-point deconvolution. The SNR value of 40 was particularly chosen as it reflects the SNR of the real Gamma-ray data, providing a reference for evaluating performance of various deconvolution algorithms.

Table 1. Comparison of real-time computation for Gamma-ray pulse processing algorithms using the TMS320C6711

Algorithm name	# of DSP clock cycles for algorithm computation
3-point deconvolution	637
3-point-deconvolution with a moving average	6527
3-point with a Savitzky Golay filter	7785
4-point deconvolution	657
4-point deconvolution with a moving average	6537
4-point deconvolution with a Savitzky Golay filter	7805
5-point deconvolution	675
5-point deconvolution with a moving average	6613
5-point deconvolution with a Savitzky Golay filter	7817

Note that there is always a trade-off between SNR performance and pileup suppression when choosing the optimum value of X. So if pileup suppression were a priority, one would tend to choose lower values of X with slight SNR degradation. However, if SNR were a priority, one would tend to select higher values of X with some degradation in pileup suppression. See Table 1 for a real-time analysis of the Gamma-ray spectroscopic algorithms using the profiler of the Code Composer Studio and the TMS320C6711 DSP evaluation board. The 3-point deconvolution filter took approximately 637 DSP CPU cycles or 4 μs in computation time using the TMS320C6711 at 150 MHz. As was expected, this was the least complex among the other entire Gamma-ray algorithms.

Benchmarking results drawn from the code composer studio, and using the TMS320C6711 evaluation board, and summarized in Table 1, shows that all of the Gamma-ray deconvolution algorithms computation times comply with the Gamma-ray spectroscopic real-time requirements. The code composer studio runs into a number of optimization phases, where the worst

Table 2. Comparison of algorithm complexity of various deconvolution techniques

Method	No of real multiplication operations required	No of real addition operations required
Inverse Wiener	$2.055 \cdot 10^4$	$2.73 \cdot 10^4$
3-point deconvolution	$3N = 1050$	$2N = 700$
3-point deconvolution + moving average prefilter	$12N = 4200$	$10N = 3500$
4-point deconvolution	$4N = 1400$	$3N = 1050$
4-point deconvolution + moving average prefilter	$13N = 4550$	$11N = 3850$
5-point deconvolution	$5N = 1750$	$4N = 1400$
5-point deconvolution + moving average prefilter	$14N = 4900$	$12N = 4200$
3-point deconvolution + Savitzky Golay prefilter	$30N = 10500$	$29N = 10150$
4-point deconvolution + Savitzky Golay prefilter	$31N = 10850$	$30N = 10500$
5-point deconvolution + Savitzky Golay prefilter	$32N = 11200$	$31N = 10850$

scenario case for real time computation is running through the whole pulse analysis plus deconvolution algorithms to extract the pulse parameters of interest, since the Gamma-ray pulses consist of a mixture of single and piled-up pulses. Taking into consideration the Gamma-ray statistics in the pulse record captured from the NaI(Tl) scintillation detector, which amounts to be approximately 15% single pulses and 85% double pulses.

Using the DSP board, the 3-point and 4-point deconvolution algorithms with the Savitzky Golay filter require approximately 52 μs. This is based on the fact that a typical Gamma record pulse tail can extend up to approximately 520 samples. Given that the TMS320C6711 is capable of performing 300 million MACs/s, the resulting computation time using a 3-point deconvolution plus the 27-point Savitzky Golay filter becomes 52 μs for the whole Gamma pulse record. With such a low computational load, the real-time constraints can easily be achieved.

4. ALGORITHMS COMPLEXITY

To compute the complexity of the different pulse identification algorithms, we needed to compute the number of real multiplications and additions performed for each algorithm based on an existing platform. For the inverse Wiener algorithm, Sam Kit Sin [12] cited that the number of multiplication operations needed is: $6N\log 2(N) + 8N$, and the number of real additions needed is: $9N\log 2(N) + 2N$, where N is the waveform record length. The original waveform record length captured at ERL is 1200 samples, but we have just taken the effective pulse width of the Gamma pulse model that includes the relevant information as 7τ. This amounts to only 350 samples, which cuts down in computation by almost 70%, since a large portion of the Gamma waveform consists of baseline (which is mostly redundant data). Table 2 shows a comparison of the number of real arithmetic operations needed by each of the pulse identification algorithms.

5. CONCLUSION

In this paper, we have developed a new approach for resolving pileup in Gamma-ray spectroscopy using deconvolution filters. Using the proposed algorithm, we were able to reduce the number of unwanted pileup events by almost eight fold (from 56% to only 7% remaining pileups). The deconvolution algorithms were successfully implemented in real-time using the TMS320C6711 DSP board for the case of an actual ^{22}Na Gamma source.

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