

Real Time Pulse Pile-up Recovery in a High Throughput Digital Pulse Processor

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Abstract. Detection and measurement of radiation is used extensively for non-invasive material characterization in a range of industries. However, many practical applications are frustrated by pulse pile-up within the detector. Pulse pile-up, which occurs when multiple radiation events arrive within the temporal resolving time of the detector, degrades the fidelity of subsequent material analysis. Traditional pulse processing techniques use fast digital filters and logic circuits to detect piled-up events and discard the corrupted data, however, this leads to substantial detector dead time. Consequently, there is considerable interest in more complex signal-processing algorithms to extend the performance of pulse processors and improve material characterization techniques. We present a technology for real-time decoding of pulse pile-up events. It is a model-based signal-processing algorithm able to accurately characterize the number, time-of-arrival and energy of all events in the detector output. Even in the presence of severe multi-pulse pile-up, the composite events are decoded and the energy and time-of-arrival recovered. The technology has been evaluated using a range of detectors, sources and count rates. An exceptional improvement over traditional pulse processing techniques is demonstrated.

Keywords: Digital pulse processing, pulse processing, pulse pile-up, pile-up.

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INTRODUCTION

Pulse pile-up is apparent in the output of a radiation detector when multiple radiation events arrive within the resolving time of the detector. As shown in Fig. 1, the detector does not have sufficient time to recover from the first detection (i.e. for the signal to return to the baseline) to accurately detect subsequent radiation events.

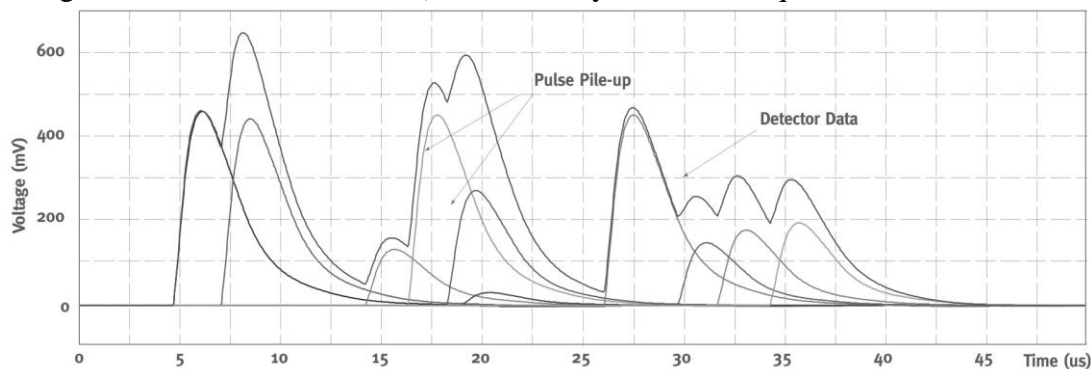


FIGURE 1. Pulse pile-up in the detector output. The signal is composed of multiple individual pulses which pile-up on top of each other making it difficult to determine the energy of an individual event.

Traditional Approaches to Digital Pulse Processing

Historically, analogue pulse shaping circuitry (i.e. pulse shaping amplifiers, delay line circuits and discriminators) has been used to analyze the output of radiation detectors. However, across the last two decades, the use of direct digitization of the detector output followed by digital pulse analysis techniques has become popular.

Advantages of digital pulse processing (DPP) include: stable operation across a wider range of temperatures and noise environments; additionally, modern digital pulse processing techniques have significantly extended the operational count rate range of detection systems. This is because more complex signal conditioning and 'optimal' filtering functions can be implemented [1].

Commonly in digital pulse processors, linear filters are used to produce trapezoidal pulse shapes with variable rise and peaking times. However, it is not possible to design such filters to produce both an optimal signal to noise ratio (SNR) and have a short duration. The short shaping times required to reduce pulse duration also attenuate signal energy resulting in a reduction in SNR, which causes a consequential degradation in full width half maximum (FWHM) energy resolution. Furthermore, these filtering techniques are unable to resolve closely spaced pulses, consequently pulse pile-up remains a problem.

While there has been significant development in the design and implementation of optimal filtering techniques for digital pulse processing, the approach for dealing with pulse pile-up in the output of radiation detectors has remained consistent for both digital and analogue systems. Generally, logic circuits are used to identify pulses that have 'piled-up' on top of each other and exclude these events from the energy spectrum. Commonly, two separate channels of processing are implemented: a fast channel to detect events; and a slow channel to accurately measure the energy. If the fast channel detects the arrival of another event within the timing resolution of the slow channel both pulses are rejected as pile-up [2]. Although this approach improves the accuracy of the spectrum, the time required to collect sufficient statistics dramatically increases. In many applications as much as 80% of information can be lost to the effects of dead time and pulse pile-up [3].

This paper presents an alternate methodology for analyzing the output of radiation detectors. Utilizing model-based signal-processing techniques, the digitised output of the radiation detector is modeled as the sum of an unknown number of events each having a random time of arrival, unknown energy and having some expected pulse shape. We present a digital pulse processing technique capable of accurately estimating each of these parameters in real-time, enabling the recovery of information from piled-up events. The performance of the technique, with a number of radiation detectors, and across a range of input count rates is also evaluated.

DISCUSSION

Recently, there has been interest in implementing more complex signal-processing methodologies to further improve detector resolution, timing and throughput at high count rates [4]. However, the performance of more advanced 'optimal' digital pulse

processing techniques has been shown to be highly dependent on the underlying assumptions of such techniques [5].

Model-based, High Throughput Digital Pulse Processing

This paper presents a non-linear, model-based, real-time, signal-processing algorithm that accounts for many of the time varying system dynamics. The algorithm characterizes the output of the radiation detector as shown in Eq. 1.

$$y[n] = \sum_{i=1}^N \alpha_i h[n - \tau_i] + \omega[n] \quad i = 1, 2, 3, \dots, N \quad (1)$$

As depicted in Fig. 2, the digitised radiation detector time series ($y[n]$) is modeled as the sum of an unknown number of radiation events (N), with random time of arrivals (τ_i), and amplitudes (α_i), interacting with a radiation detector, that have an expected pulse shape ($h[n]$) and with a noise process ($\omega[n]$). Therefore, so as to fully characterise the digitised output of the radiation detector, it is necessary to estimate: the expected impulse response of the detector; the number of events in the digitised detector time series; the time-of-arrival of each of those radiation events; and the individual energies of each event. Once these parameters have been determined, the digitised detector data can be accurately decomposed into the individual component events and the energy of each event determined.

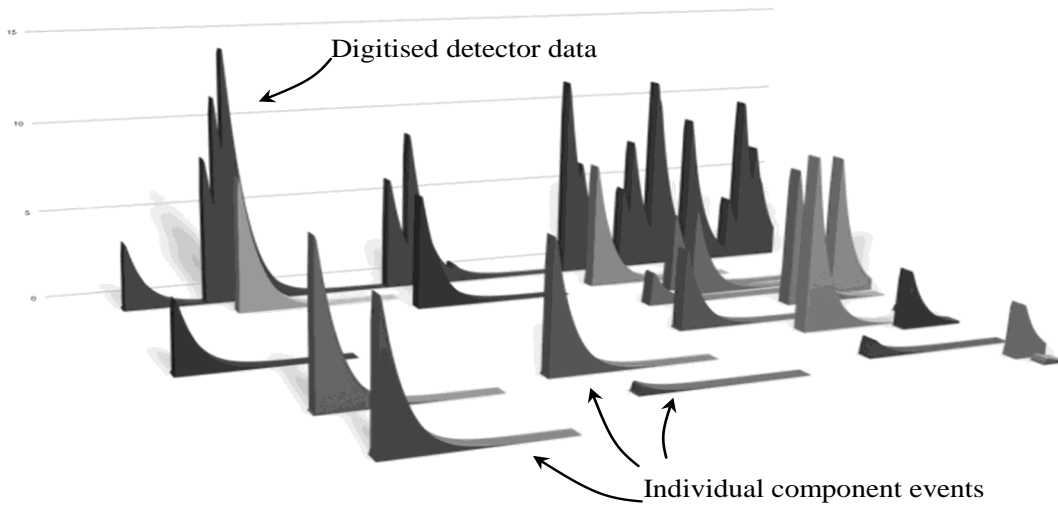


FIGURE 2. Schematic showing that the digitised detector data is in fact a summation of multiple events of distinct energies interacting with the detector at different time-of-arrivals.

The model of the digitised detector time-series from Eq. 1 may also be written in matrix form as

$$Y = A\alpha + \omega, \quad (2)$$

where A is a $m \times N$ matrix. The entries of the matrix are given by

$$A(n,i) = \begin{cases} d(n - \tau_i) & \tau_i \leq n < \min(m, \tau_i + T - 1) \\ 0 & \text{otherwise} \end{cases}, \quad (3)$$

where T is the length of $d[n]$ in samples (the detector impulse response) and m is the total number of samples in the digitised signal $y[n]$. Additionally, α is the vector of N signal energies and $\omega[n]$ the discrete time form of the noise with length m .

Thus, the columns of matrix A contain multiple versions of the unit detector impulse response. For each of the individual columns, the starting point of the unit detector impulse response is defined by the time-of-arrival of that particular event. By solving Eq. 2 for the N individual energy values, this approach is able to decode pulse pile-up events in real-time, accurately characterizing the number, time-of-arrival and energy of all events in the detector output.

The Pulse Pile-up Recovery Algorithm

The pulse pile-up recovery algorithm is illustrated in Fig. 3 and operates directly on the digitised output of the detector. In this specific implementation, the detector output signal is digitised at 60 MHz using a 16-bit analogue to digital converter (ADC).

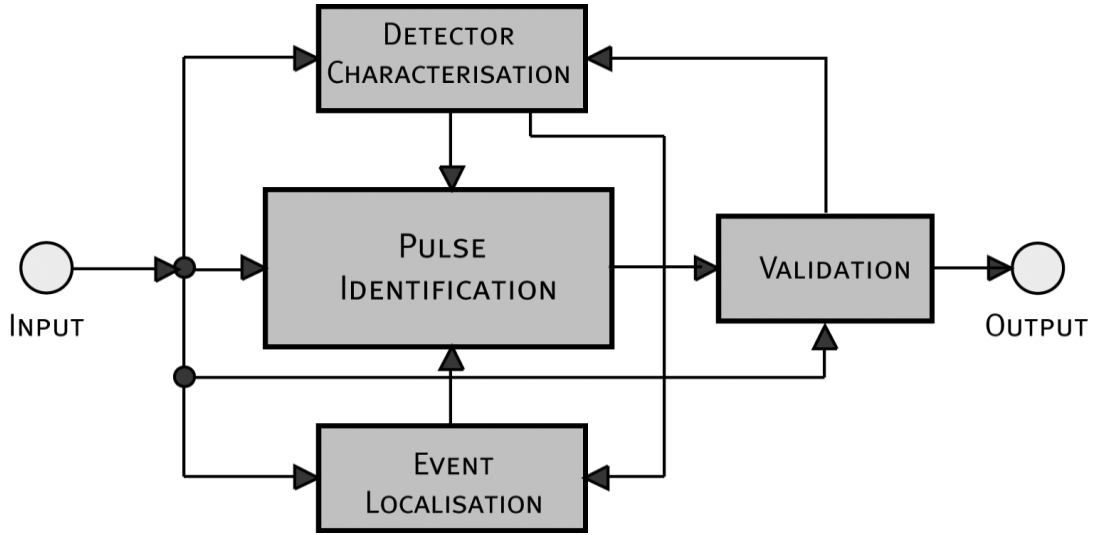


FIGURE 3. A functional overview showing the stages of the pulse pile-up recovery algorithm.

Detector Characterization is the first stage of the algorithm; it takes as input the detector time series data and determines the unit impulse response of the detector (the pulse shape expected from the detector). Data is collected under the constraint of a low input count rate ($< 10,000$ c/s) in order to minimize the probability of pile-up events. The unit impulse response is constructed by averaging a large number of individual radiation events.

Subsequently, the impulse response is used by the Event Localisation stage to find the number and time-of-arrival of each event in the data stream. As Fig. 4 illustrates, it is important not to constrain the event arrival time to integer values of the ADC

sampling. Due to the asynchronous relationship between the ADC clocking and the arrival time of a radiation event it is important to account for intra-sample arrival times. Fig. 4b) depicts the error in the reconstruction model when one assumes integer arrival; this error degrades the overall performance of the algorithm. Accounting for intra-sample event arrival (by interpolating the detector impulse response across 2 consecutive samples) the residual error in the fitting of the model to the data is substantially reduced, as depicted in Fig. 4c).

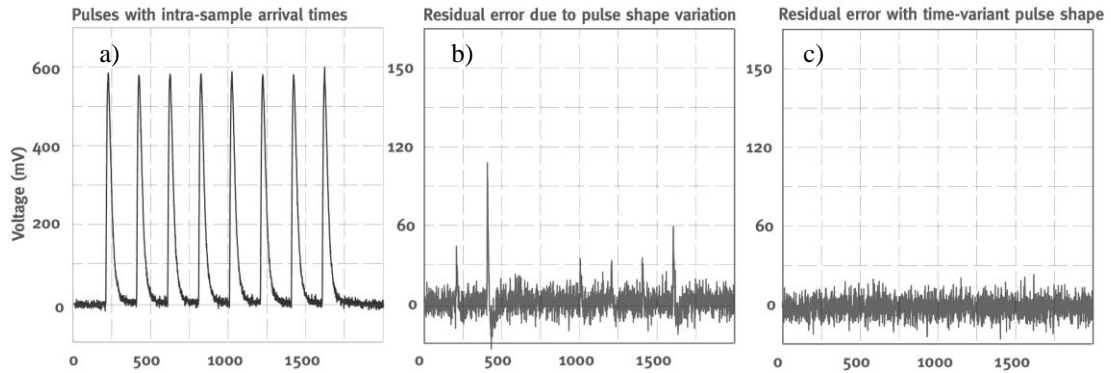


FIGURE 4. A functional overview of a numerical simulation scanning the arrival of a radiation event across two sampling points with each having four sub-sample time of arrival position.

By harnessing the *a priori* knowledge of the expected pulse shape and interpolating between ADC samples, the Event Localisation stage uses finite impulse response filters (FIR) to determine very accurately the number and arrival time of each radiation event. Using the 60 MHz 16-bit ADC events can be time stamped with 4 ns accuracy, a dynamic range (the ratio of smallest to largest energy events detected) of over 600 has been demonstrated.

The Pulse Identification stage determines the energy of all the radiation events in the detector data stream. As its input it uses: (a) the *a priori* knowledge of the detector unit impulse response; (b) the number of events; and (c) their individual time-of-arrival data obtained from the Localisation stage.

The final functional stage of the real-time signal-processing algorithm is the Validation stage. As depicted in Fig. 5, at this stage all the parameters that have been estimated by previous algorithmic stages (pulse shape, number of events, time-of-arrival and event energy) are combined to reconstruct a 'noise-free' model of the detector data. By subtracting this model of the detector data from the actual digitised detector time series, the accuracy of the estimated parameters can be determined. Much like examining the residual from a straight line fit of a data set, if the magnitude of the residuals is small, the parameters well describe the data. However, if at any point large residuals are observed, the detector data has been poorly estimated and that portion of the data can be rejected.

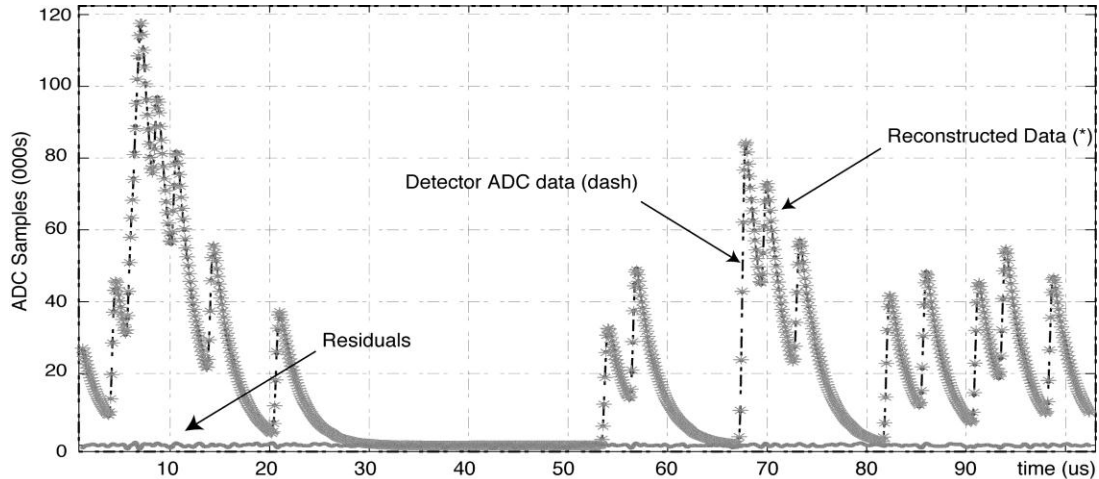


FIGURE 5. A ‘noise-free’ model of the detector data is reconstructed by the “Validation” stage using the parameters which have been determine from previous stages of the algorithm.

EXPERIMENTAL SETUP AND RESULTS

The real time performance of model-based parameter estimation and its application to digital pulse processing have been evaluated using both scintillation based and semiconductor based radiation detectors.

Algorithm Performance Using a Scintillation Detector NaI(Tl)

To evaluate the efficacy of the technique with scintillation detectors, a 51 x 51 mm NaI(Tl) detector from Scionx was used. Secured on a movable mount, the detector was irradiated with a collimated beam of gamma-rays. The flux of gamma-rays through the detector was adjusted by using three different ^{137}Cs sources of varying strength (0.37 GBq, 3.7 GBq and 37 GBq) and also by adjusting the distance between the source and the detector.

The output from the anode of the photomultiplier tube was connected to a wide band current amplifier (FEMPTO model DHPKA 100). The output of the FEMPTO amplifier was fed directly into the pulse processing hardware, which digitised the voltage signal using a 14-bit, 60 MHz ADC. The digitised detector data stream was processed in real-time on a Virtex-4 SX 35 field programable gate array (FPGA)

The real-time performance of the pulse pile-up recovery algorithm is illustrated in Fig. 6 (in terms of FWHM energy resolution and dead-time) with increasing input count rate. Despite a 30-fold increase in input count rate, from 50 kc/s to 1500 kc/s, the detector dead time shown in Fig. 6a) remains less than 10%. The FWHM detector resolution for the 662 keV energy peak from ^{137}Cs , shown in Fig. 6b), degrades by less than 25% from a minimum of 6.8% to a maximum 8.9%.

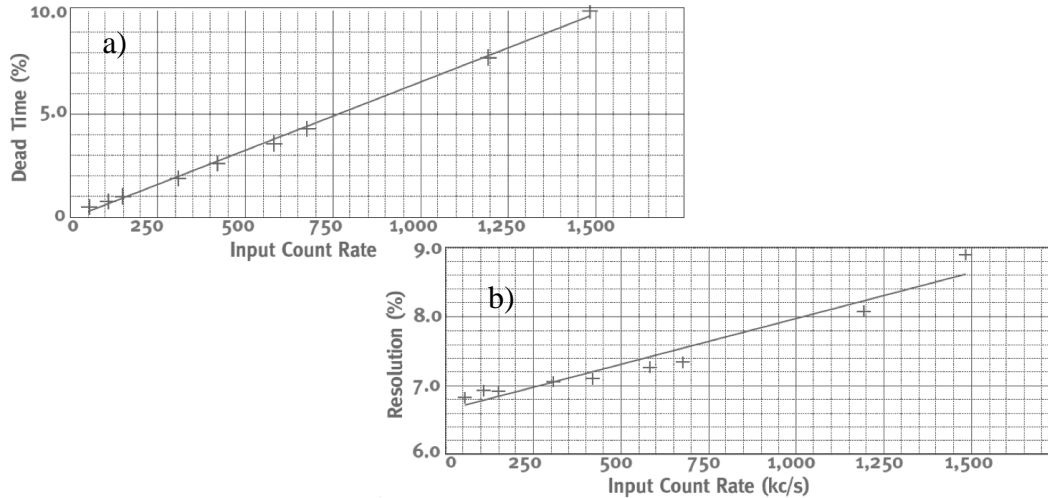


FIGURE 6. The performance of pulse pile-up recovery algorithm vs. input count rate. Up to a input count rate of 1500 kc/s detector dead time is below 10% and detector energy resolution less than 9%.

Algorithm Performance Using a Silicon Drift Diode Detector

The performance of the real-time pulse pile-up recovery algorithm has also been evaluated with semiconductor based radiation detectors, specifically a 7 mm² silicon drift diode (SDD) detector manufactured by Ketek GmbH of Germany.

The output from the charge reset amplifier of the SDD detector was passed through a CR shaping network to produce a nuclear decay pulse of approximately 12 μs in duration. This signal was then conditioned using the FEMPTO DHPKA 100 amplifier to ensure that the peak of interest (the 5.9 keV peak from ⁵⁵Fe) equated to approximately 30% of full scale of the ADCs (approximately 300 mV). An ⁵⁵Fe isotope source was secured to a movable mount and the source-to-detector distance controlled very accurately by a stepper motor. Using this experimental setup, it was possible to accurately and repeatably control the source-to-detector distance to less than 0.02 mm.

As depicted in Fig. 7, using this setup, the input count rate could be varied across a range of 10-194 kc/s. Across a 20-fold increase in input count rate, the detector dead-time remained below 10% (a) and the FWHM energy resolution degraded by 12% (b).

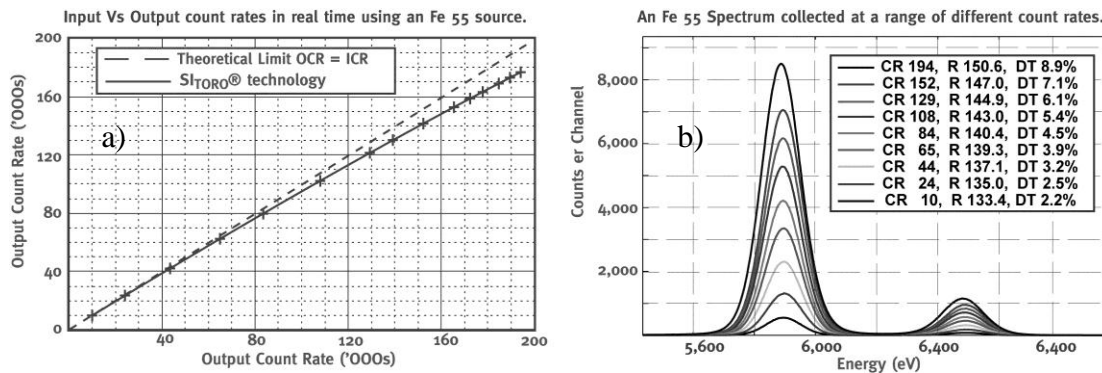


FIGURE 7. The performance of the pulse pile-up recovery algorithm used in conjunction with a 7 mm² silicon drift diode detector from Ketek.

IMPLEMENTATION

The real-time pulse pile-up recovery algorithm has been designed and implemented in a Xilinx FPGA on an electronics board designed with and sold by XIA (shown in Fig. 8). All the data processing modules are implemented on-board and communication with the host is provided via either an Ethernet or a fast USB 2.0. The very high rate USB 2.0 communications protocol not only enables list mode operation (the energy and time-of-arrival of detected events are passed up to the PC for further processing) but also enables the card to work as a digital oscilloscope. Digitised detector data can be uploaded to the host computer at > 30 MB/s.

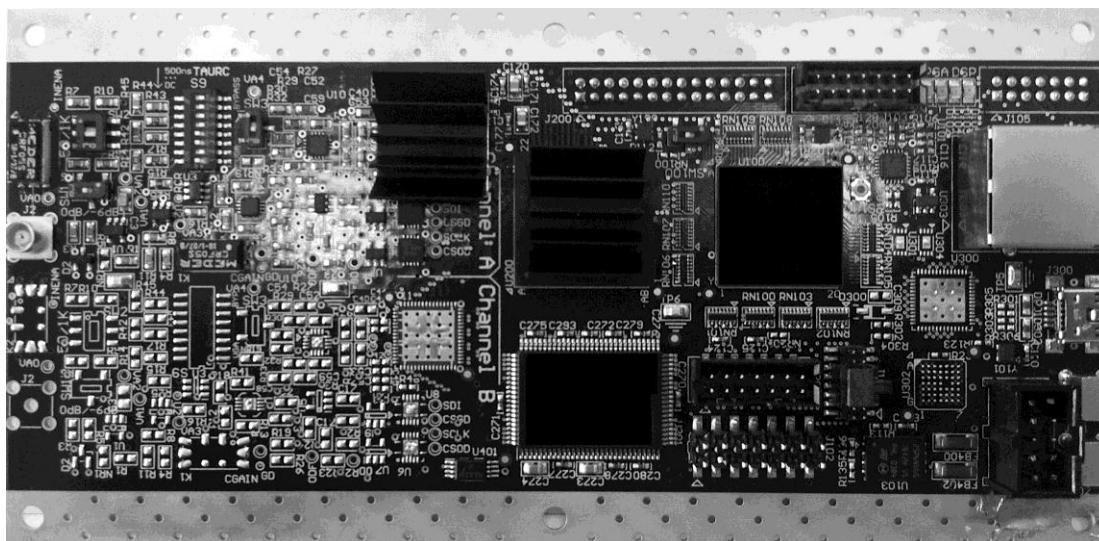


FIGURE 8. A nuclear electronics board designed for the real time pulse pile-up recovery algorithm.

CONCLUSION

A model-based digital pulse processing technique has been presented that enables high throughput low dead-time pulse processing by recovering rather than discarding data corrupted by pulse pile-up. The algorithm has been implemented in real-time and its performance evaluated with a range of radiation detector types. Key performance metrics include: a throughput in excess of 1500 kc/s; very low dead-time; little degradation of resolution at high count rates; real-time decoding of multi event pulse pile-up; and pulse pair resolution less than 50 ns.

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