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Event by event pile-up compensation in digital timestamped calorimetry

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ABSTRACT

In digital nuclear calorimetry, the effect on measured pulse amplitudes by piling up of pulses can be compensated based on the pulses' respective timestamps, making use of the fact that, for stable pulse shapes, the amount of pile-up induced error at each pulse amplitude measurement is completely determined by the amplitudes and precise occurrences in time of the neighboring pulses. We propose here a compensation method, based on the above observation, suitable for real-time as well as off-line implementation. Successful tests performed off-line both on synthetic and experimental data are shown as a proof of principle. We further propose a draft architectural approach to real-time compensation schemes of this functionality and the corresponding interaction with the experimental controls.

1. Introduction

The design of front-end electronics (FEE) of the coming generation of nuclear spectroscopic instruments is almost universally homing in on the paradigm of a freely running analogue to digital (AD) conversion and real-time front-end digital analysis. The latter provides algebraic self-triggering within each read-out channel and reports over a digital link a stream of events, usually referred to as 'list mode' data. Each reported event consists of at least a pulse magnitude measurement and a timestamp. The latter is most commonly the value that a local counter, synchronous to the AD converter clock, had at the moment of pulse detection.

At per-channel count rates approaching the scale equivalent to the inverse pulse width, it becomes increasingly probable that pulses pile-up, i.e. that a measurement of a pulse magnitude is in error because of an almost simultaneous occurrence of another pulse. This results in systematic distortions of the measured pulse height spectra, yielding ghost summation peaks, systematic shifts of spectral peak positions, as well as artificial spectral continuum contributions. All these artifacts come at the expense of reduced true-energy efficiency, i.e. a reduced number of correctly measured pulse heights.

The precise extent of pile-up related artifacts on energy measurements can to a certain extent be reduced by appropriate choices of integration weight functions. However, this comes at the expense of suboptimal amplitude measurements, as discussed in Ref. [1], or, for instance, introduces a strong dependence of measured amplitudes on the temperature of the scintillation crystal [2].

In this paper we propose an approach which takes advantage of timestamps initially obtained in the signal analysis for the individual pulses underlying the measured signal, to correct for pile-up related errors in the measurement of pulse heights.

2. Description of the method

We assume the simplified case of a series of pulses with a stable shape $p(t)$, superimposed on a zero baseline. An individual i-th pulse with the amplitude a_i occurring at time t_i is modeled as $p_i(t) = a_i p(t - t_i)$. Choosing the time unit equal to the sampling period, the AD conversion results in a stream of digitized signal values, one per each integer time. We use this discrete time axis throughout the rest of this study, and the signal can then be described as a sequence over integer t:

$$s(t) = \sum_i a_i \cdot p(t - t_i). \quad (1)$$

The zero baseline condition assumed above for transparency does not represent a fundamental requirement and can be abandoned by choosing appropriate baseline handling. An option would be application of a baseline follower based on an appropriate low-pass digital filter, dynamically inhibited during presence of a pulse [3,4]. Alternatively, for long decay time scintillators such as CsI(Tl), where the baseline might fluctuate significantly during a single pulse, carefully designed bandpass digital filters with little

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or no DC response could be used to suppress the effect to a large extent while reducing the pile-up as well.

Digital calorimetry generally works by estimating the pulse size via a weighted sum of digitized points in the vicinity of each pulse peak. This summation is often structured as a Finite Impulse Response (FIR) filter with coefficients $f(k)$, resulting in a filtered signal

$$q(t) = \sum_k f(k)s(t-k). \tag{2}$$

Presence and timing t_i of the i-th pulse within a digitized stream $s(t)$ are determined by a triggering algorithm used. We assume that the timestamp t_i can be extracted unaffected by the presence of pile-up, as argued later on. The timing information provided by the trigger defines up to a constant lag l the readout point in the filtrate sequence $q(t)$ for amplitude estimate b_i (Fig. 1). The lag l is commonly chosen so that the latter are picked close to maxima of filtered pulses. Note also that, unlike in classical spectroscopy electronics, this approach must not inhibit triggering during pulse duration; to detect all pulses, it is crucial that 'dead time' is kept essentially at zero.

Each amplitude estimate b_i is thus defined by

$$b_i = \sum_j \left(\sum_k f(k)p(t_i - t_j + l - k) \right) a_j \tag{3}$$

which exposes b_i as a linear combination of signal amplitudes a_j of all pulses present through filtering at the i-th amplitude readout point. In matrix notation of the same,

$$\mathbf{b} = \mathbf{Ma} \tag{4}$$

with the matrix elements of $\mathbf{M}$ defined as

$$M_{i,j} = m(t_i - t_j + l) \tag{5}$$

with

$$m(t) = \sum_k f(k)p(t-k). \tag{6}$$

Note that the matrix elements $M_{i,j}$ are simply model pulse filtrates $m(t)$ at points governed by the timestamp differences.

Given a set of measurements $\mathbf{b}$, the inverse transformation must unveil the original $\mathbf{a}$. This is a well behaved linear problem in modest pile-up regime, where only a small fraction of each b_i is due to intermixed neighbors, rendering $\mathbf{M}$ a sparse, dominantly diagonal matrix. Approaching severely piled-up cases, meaning nearly coinciding timestamps, however, introduces two significant origins of uncertainty to the reconstructed amplitudes.

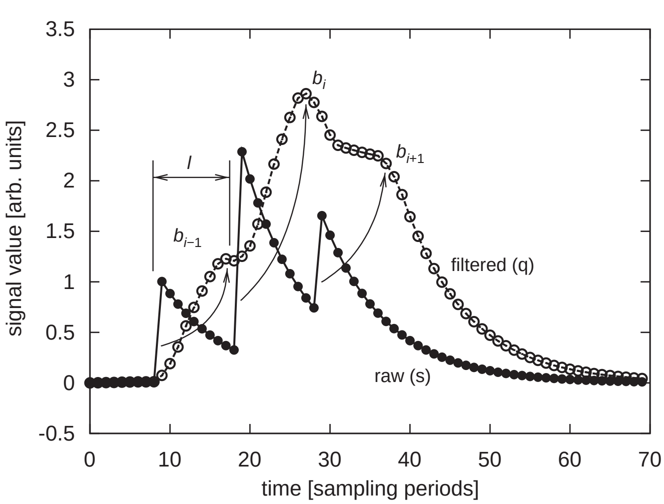

Fig. 1. Digital calorimetry; separately obtained timestamps t_i define, up to a constant lag, points in the filtered signal which serve as initial amplitude estimates b_i. The arrows indicate the constant-lag definition of b_i in the filtered signal, relative to the triggering feature in the original signal.

Firstly, the linear problem becomes ill-conditioned. This makes relative uncertainties of a_i strongly anti-correlated and the resulting relative errors in a_i become much larger than the relative errors of measured $\mathbf{b}$. Most of the information available in $\mathbf{b}$ is thus a measure of the *sum* of the amplitudes $\mathbf{a}$ of overlapping pulses, while a lesser amount of information is left for the difference between them.

Further, the transformation coefficients $M_{i,j}$ themselves are estimated values affected by the detector physics and the readout chain noise which both induce instabilities in the pulse shapes used in the construction of $m(t)$. However, the fact that the latter is constructed from *filtered* average pulse shapes greatly reduces this uncertainty. Another systematic source of error is that of the neglected temporal uncertainty of timestamps propagating into the matrix elements $M_{i,j}$ and presumably becoming more important with increasing rates. Since detection physics as well as signal analysis optimization promote the assignment of time-stamps to the leading edge of pulses, which commonly can be considered short in comparison to the trailing edge, we consider timestamps in the present context a robust invariant.

In principle an infinite linear problem (the number of pulses per data acquisition channel in an experimental run defines the dimensionality of the linear system!) simplifies significantly due to the dominantly band-diagonal nature of $\mathbf{M}$. The diagonal elements form an identity and describe the ideal measurement response with no inter-pulse mixing, while off-diagonal elements measure cross-influence of piled-up pulses. Well behaved enough, due to the nature of spectroscopic pulses, $M_{i,j}$ tend to vanish exponentially for $i \gg j$ and truncate to zero for $j \ll i$, which allows for computationally light sliding-window approaches to the problem of inversion, discussed in the next section. Further, the function $m(t)$ does not depend on the statistics of incoming pulses, for a given pulse shape and filter properties. It can therefore be tabulated in advance to facilitate fast real-time linear system definition.

Complementary to prior approaches (see for instance Ref. [5]), the presently proposed pile-up reconstruction has the potential to work in real time on an event by event basis, rather than on a collected spectrum, thus inherently a posteriori. The approach also does not assume any specific time structure of the incident radiation flow. Other event based approaches do have a comparable resolving potential, but tend to be more demanding on the readout and DAQ bandwidths, mass storage capacities, and off-line computing, such as the 'store and study' scheme of Ref. [6], or numerically somewhat heavy for real-time processing [7].

3. First neighbor approximation (FNA)

For the purpose of the rest of this publication, we consider an approximative implementation of the above scheme in which each measured b_i is affected by at most one closest neighbor on each side. Further, for argument clearness, we normalize the matrices by dividing all elements by $m(l)$. This exposes the identity nature of $\mathbf{M}$ in the low count rate limit, while trivially changing the overall spectrometer gain. The mixing of the triplet of pulses $i-1$, i, $i+1$ is then described by

$$\begin{pmatrix} 1 & p & 0 \\ r & 1 & q \\ 0 & s & 1 \end{pmatrix} \begin{pmatrix} a_{i-1} \\ a_i \\ a_{i+1} \end{pmatrix} = \begin{pmatrix} b_{i-1} \\ b_i \\ b_{i+1} \end{pmatrix} \tag{7}$$