High Rate Pulse Processing Algorithms for Microcalorimeters

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***Abstract*–Microcalorimeters, cryogenic radiation detectors measuring the energy of photons by the increase of temperature in an absorber, can achieve energy resolutions more than an order of magnitude better than HPGe detectors. However, due to the thermal nature of the pulse generation, the active volume has to be small to maintain good resolution, and pulse decay times are in the order of milliseconds. Consequently, the detection efficiency is low and count rates are limited, especially for commonly used "optimum filter" algorithms that require isolated pulses to measure pulse heights. This is typically solved by building systems with multiple detector elements (arrays). Large arrays, however, require that as much pulse processing as possible be performed at the front end of the electronics to avoid transferring large amounts of waveform data to a host computer for processing.**

Pulse processing algorithms developed by XIA LLC for use in digital spectrometers with HPGe detectors, suitably modified for the slower time scale, meet this requirement. In the work reported here, we offline-processed microcalorimeter pulse streams with modified HPGe filter algorithms to provide an initial engineering evaluation of their performance as "practical" filters, capable of achieving sufficiently good energy resolution for most applications while being a) simple enough to be implemented in the readout electronics and b) capable of processing overlapping pulses and thus of achieving higher count rates. In the course of this work, a new filter was developed that uses only a fraction of a pulse while still achieving good energy resolution for very high count rates. The success of this work suggests that future microcalorimeter read-out systems can indeed be built with electronics on which these filters are implemented in multiplexed form, taking advantage of high speed digital signal processing elements to process many channels in parallel at a large reduction in processing cost per channel.

I. INTRODUCTION

MICROCALORIMETERS are cryogenic radiation detectors that measure the energy of photons or particles by the increase in temperature of an absorber. The thermal sensor is typically either a thermistor or a superconducting transition edge sensor (TES), operating at temperatures of ~0.1K. Microcalorimeters can be used as very precise detectors for electromagnetic radiation from microwaves to gamma rays. Their energy resolution is fundamentally limited only by the ratio of the measured temperature rises to the value of thermodynamic temperature fluctuations. For example, a microcalorimeter for gamma-ray spectroscopy can achieve a resolution well below 100 eV in the energy range of 100 keV. Energy resolution as good as 22 eV FWHM at ~100 keV has recently been demonstrated by a NIST/LANL collaboration [1].

A microcalorimeter typically consists of a bulk absorber with a certain heat capacity attached to a TES, both of which are weakly coupled to a cold bath (see inset in Fig. 1). An x-ray impinging upon the absorber will increase the absorber's temperature by an amount proportional to the x-ray energy. The temperature increase can be measured with the attached TES thermometer before both the absorber and TES cool back down to the bath temperature through the weak thermal link. The TES operates on the steep part of the superconducting-to-normal transition curve from zero to finite resistance (Fig. 1), which ensures high sensitivity of the temperature measurement. It is typically read out by a SQUID magnetometer measuring the current flowing through the TES at a constant applied voltage. As the resistance of the TES increases when its temperature increases after being hit by a gamma ray, the current through the TES decreases, which reduces the magnetic field from a series inductor monitored by the SQUID. The SQUID signal is then amplified in a preamplifier stage (at room temperature) and passed on to the pulse processing electronics. The preamplifier noise and Johnson noise can be kept sufficiently low to leave the energy resolution limited only by the fundamental thermodynamic principles.

The size of the cryogenic gamma-ray detectors that can achieve 100 eV energy resolution is intrinsically limited to roughly 1 mm^3 per pixel and therefore the detector efficiency is low. In addition, the maximum count rate is limited by the slow thermal decay time and the currently used "optimum filter" pulse processing algorithms that require isolated pulses to measure pulse heights. These challenges can be (partially) addressed by fabricating large detector arrays with $10^2 - 10^3$ or more pixels. However, the increased number of channels in turn requires that the pulse processing be performed as much as possible at the front end of the electronics to avoid transferring large amounts of waveform data to a host computer for processing.

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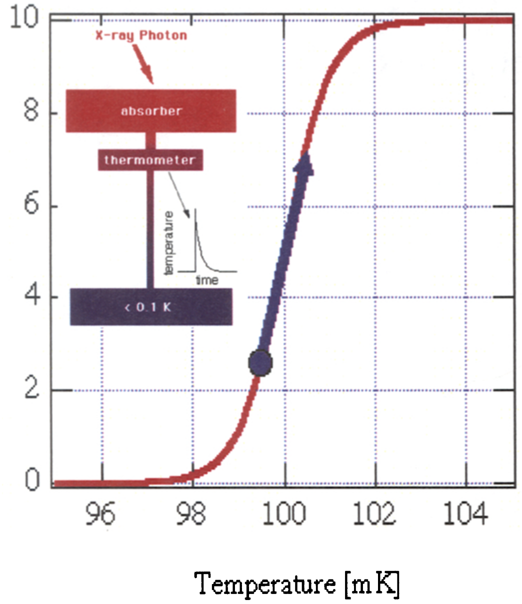

Fig. 1. Resistive transition between the superconducting and the normal state of a transition edge sensor (TES). Detector operation in the steep part of the transition ensures high sensitivity. The inset shows a schematic design of a single TES detector.

The signals from microcalorimeters are very similar to those output by conventional HPGe detectors, except that they are approximately three orders of magnitude slower. XIA's digital spectrometers for HPGe detectors employ trapezoidal or integral filters that typically use only a fraction of the pulse decay and thus are capable of processing overlapping pulses (as long as they are separated by more than the filter time) at high count rates [2]. With HPGe detectors, these filters can achieve energy resolutions of 0.1% or better when the intrinsic detector resolution is not the limiting factor, i.e. in high energy regions. Furthermore, as they are implemented in on-board digital signal processing elements in the readout electronics, only accumulated spectra or lists of computed pulse heights have to be transferred to the host PC. Consequently, even though their resolution may not be as good as that of a mathematically-provable optimal filter, the benefits of higher achievable count rates and being easily implemented in readout electronics mean that these filters offer significant promise for use in a practical and efficient microcalorimeter detector array system, as long as their resolution is sufficient for most common applications (e.g. being able to separate close lines in isotope analysis). To perform an engineering evaluation of this key condition, we adapted our filters for the slower time scale of microcalorimeters and applied them offline to waveforms acquired from a soft X-ray microcalorimeter (NIST/NASA) and a gamma-ray microcalorimeter (LANL/NIST). Results for other detectors will be reported elsewhere. As offline analysis requires processing large amounts of waveform data and this work was intended only as an initial evaluation of the suitability of XIA's algorithms, we used only moderate file sizes and the resulting spectra have limited statistics. We will perform future work on larger data sets to provide more accurate results.

II. FILTER ALGORITHMS

XIA analyzers employ digital filters belonging to a widely known class of trapezoidal filters [2][3]. These filters are finite impulse response (FIR) filters that compute weighted finite difference of a signal. Fig. 2 shows the response of a typical trapezoidal filter used in the XIA pulse processing electronics. Fig. 3 shows the response of an integral filter. A common feature of these filters is the subdivision of the total filter window into several sub-windows in which running sums are constantly calculated.

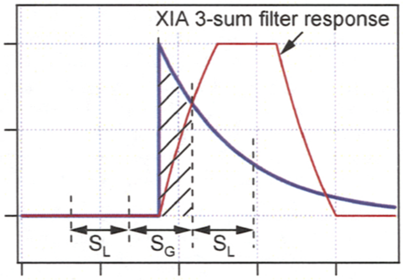

Fig. 2. Response of a typical trapezoidal filter used in the XIA pulse processing electronics.

The response of the filter is the linear combination of the running sums weighted by the appropriate coefficients depending on the filter design. The pulse energy is estimated as a difference between the filter's response on a pulse and its averaged response computed elsewhere in the absence of a pulse.

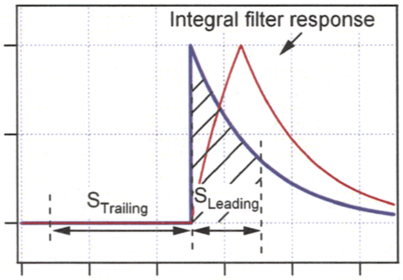

Fig. 3. Response of the integral filter.

Fig. 4 shows the basic principles employed in the design of the edge filter recently developed at XIA to analyze microcalorimeter data at high count rates. The edge filter is an FIR filter based on linear least squares parameter fitting. The rising edge of a pulse is fitted with a line within a time window **L** chosen to optimize the energy resolution. The two independent degrees of freedom of the line, its slope and its intercept, are proportional to the energy and the DC offset (baseline) of the pulse, respectively.

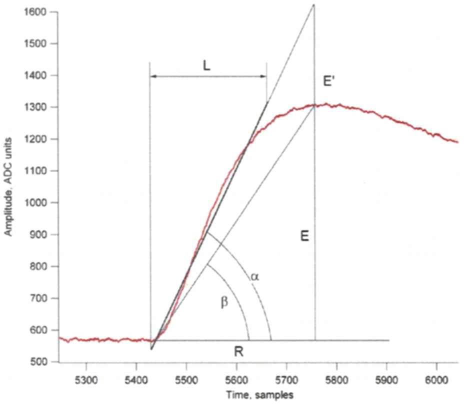

Fig. 4. The edge filter.

III. PRELIMINARY RESULTS

Fig. 5 shows our analysis of ^{55}Fe data from a pixel in a NASA microcalorimeter array [4] embedded in a NIST time-division multiplexer. The pulse decay time is about 1.3 ms and the count rate was about 1 count/s. Using an integral filter that measured the energy using only 1 ms of pulse data, we achieved a FWHM of nominally 3 eV (0.051%) for the 5.9 keV Mn K_α X-ray line for this particular small data set. This resolution is comparable to the results obtained at NIST using Wiener filters. However, since the integral filter uses only about one decay time of data it has a much smaller dead time than an optimum filter that requires fully isolated pulses (separated by several decay times), and so can achieve accordingly higher output count rates. In the future, we will attempt to replicate these results with large data sets.

Using this same data set, we also investigated the trade-off between processing time and energy resolution for simple trapezoidal filters. The results are shown in Fig. 6, where the upper curve plots energy resolution versus total filter length (i.e. $T_{total} = 2 * T_{peaking} + T_{gap}$). As may be seen, there is a significant region over which the energy resolution is nearly independent of filter length, with only a loss of 10-20% in FWHM (1,000 to 2,700 μs). The lower portion of the figure shows the maximum theoretical count rate (MTCR) for these processing times (assuming that non-linearities associated with overlapping pulses do not result in unacceptable energy resolution degradations). As Fig. 6 shows, over the same region where energy resolution might degrade by 15% (i.e. from 0.12% to 0.14%), the potential gain in throughput is enormous (from 350 cps to 1,200 cps). We note that the overall resolution using trapezoidal filters is not as good as from our integral filter, probably because our trapezoidal filter relies strongly on the assumption of single exponential decay whereas the actual microcalorimeter pulses appear to have multiple exponential decay components.

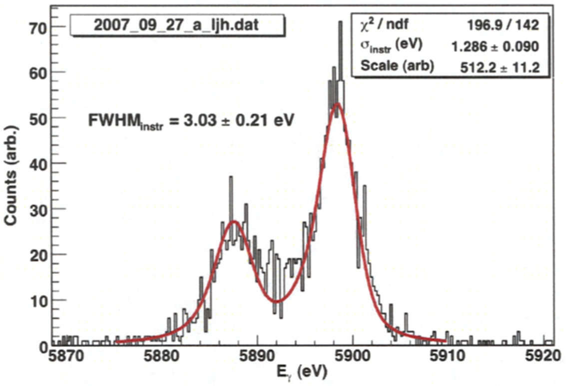

Fig. 5. Mn K_α X-ray spectrum obtained by processing NIST/NASA data offline with an integral filter. The red curve is a least square fit convolving the natural line widths to a Gaussian instrument response function. While the accuracy of the resulting 3 eV instrumental FWHM is clearly limited by statistics, the $K_{\alpha 1}$ and $K_{\alpha 2}$ lines are definitely resolved.

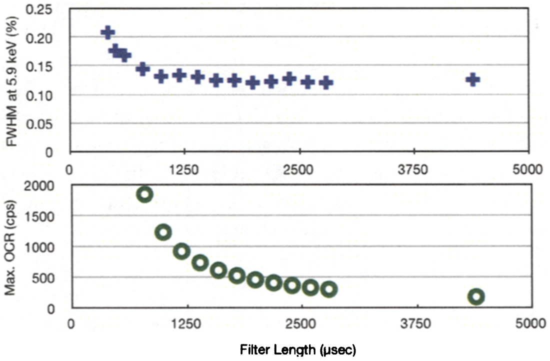

Fig. 6. (upper) FWHM versus XIA trapezoidal filter length for processing NIST single pixel data. (lower) Maximum Theoretical maximum throughput (MTCR) for the same filter lengths.

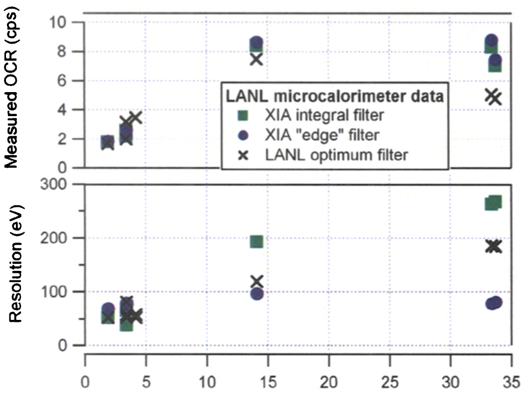

Fig. 7. Resolution and measured output count rate (OCR) vs. input count rate for XIA edge, integral filters and LANL optimum filter applied to LANL data (^{241}Am).

Fig. 7 shows resolutions and output count rates as a function of input count rate for data acquired at LANL with an ^{241}Am source. The pulse decay time was about 2.4 ms. Output count rates were limited to about 8 counts/s by the acquisition system. At low input rates, integral filter resolutions reach 38-52 eV for the 59 keV peak, though with low statistics. This is comparable to the about 52 eV LANL achieved when processing these same data sets. At high rates, the edge filter maintains good resolution (80-100 eV, versus 120-180 eV from the LANL processing on the same data sets) while achieving higher throughput and using only the pulses' rising edges to determine their pulse heights. In an acquisition with a modified XIA digital spectrometer, recording events at higher count rates, the edge filter was able to maintain an energy resolution below 160 eV for output count rates up to 33 counts/s (rates limited by the source and detector efficiency).

IV. CONCLUSIONS AND OUTLOOK

While "optimum" filters are mathematically provable to provide the best energy resolution under ideal conditions, we have shown here, by processing a variety of real experimental data sets, that a class of filters that were derived from algorithms originally developed for HPGe pulse processing and are much simpler to implement in large arrays also appears to be capable of producing acceptable results (energy resolutions well below 0.1% at low count rates). Both the edge and the integral filters use only data "local" to each pulse. This, plus better handling of overlapping pulses, may be of advantage in non-ideal conditions and in applications where the desire to operate at high counting rates or with very large numbers of detectors outweighs the need for the best possible resolution. Future work with much larger data sets will seek to provide a more definitive description of their capabilities.

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