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Technique for Recovering Pile-up Events from Microcalorimeter Data

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Abstract

We report here a technique for processing microcalorimeter data that offers improved live-time over conventional optimal filtering techniques without loss of spectral resolution. Separate filters optimized for pulse amplitude and pulse arrival time (constructed in the usual way from the averaged signal and noise spectral densities) are applied to the entire pixel data stream. Pulses in the resulting filtered streams are then simultaneously fit as the sum of scaled and shifted copies of an isolated filtered pulse template. Analysis using calibration data from the University of Wisconsin/Goddard Space Flight Center X-ray Quantum Calorimeter (XQC) sounding rocket payload demonstrates the ability of this technique to recover pulses separated by as little as the rise-time of the detectors without observable spectral broadening.

Keywords

microcalorimeter; optimal filtering; pile-up

1 Introduction

Conventional optimal filtering techniques [1] require pulses produced by individual photons in a single pixel to have a minimum separation of at least the time-domain length of the optimized Wiener filter being used. This length must typically be many times the thermal decay time (τ) of the detectors in order to achieve the best spectral resolution, as longer filters are more efficient for optimizing the signal to noise ratio (particularly when the noise spectrum contains features). However, longer filters also increase the number of pile-up events. These pile-up events (Fig. 1) cannot be processed by conventional optimal filtering, resulting in low live-time at relatively modest count rates. Consequently, a compromise must usually be made between the desired spectral resolution and the corresponding reduction in live-time when choosing the filter-length. In response to this problem, we have further developed the technique reported in Crowder et al., 2012 [2] capable of recovering pile-up events without loss of spectral resolution.

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2 Optimal Filtering

Separate filters optimized for pulse amplitude and pulse arrival time are constructed from the averaged signal and noise spectral densities, with the usual assumption that the noise is stationary during the pulse [1]. In the high signal to noise limit, the global maximum of the amplitude filter output occurs at the pulse arrival time. Therefore, the arrival time filter is chosen to maximize the slope of the signal relative to the noise. In frequency space, the Derivative Theorem for Fourier Transforms states that this is simply $-2\pi i f$ times the amplitude filter. Since the efficiency of the technique presented here does not depend on filter length, this work uses a filter length of 800 ms, with the pulse arrival placed at 200 ms. (This is four times longer than the filter length typically used for the conventional processing of XQC data.) Rather than convolving these filters with short, individually triggered data segments containing a single pulse, the filters are both convolved continuously with the entire pixel data stream. These convolutions can be done efficiently through the use of Fast Fourier Transforms and the Convolution Theorem. For an isolated pulse, the zero crossing of the arrival time convolution gives the best estimate of the pulse arrival time, and the value of the amplitude convolution at this time gives the best estimate of the pulse amplitude; there is no additional information in any of the other points (Fig. 2). There is substantial ringing at times up to the filter length away from the pulse, but this is entirely deterministic given the amplitude and arrival time. Pulses are discovered iteratively as local maxima in the amplitude convolution that exceed a threshold which is lowered with each iteration. This process of first detecting and subtracting the largest pulses avoids mistaking the ringing for additional pulses.

3 Fitting Pile-up Events

Templates for an isolated pulse are made by convolving each filter with the average signal shape (Fig. 2). Provided that the detectors are sufficiently linear that the pulse shape is not changing significantly as a function of energy, a filtered data stream containing overlapped pulses will simply be the sum of the properly scaled and shifted templates (non-linearities limited to pulse amplitude can be corrected after fitting without loss of resolution, as will be discussed below). For a time interval containing N pulses, one must solve for the set of N arrival times and N amplitudes that match exactly the $2N$ observed filtered data points at these arrival times (Fig. 3). In practice, this exact solution is found numerically with a Levenberg-Marquardt least squares algorithm, since the estimation of pulse arrival times lacks an analytic solution. The least squares fitting is the most computationally intensive step of this technique and stands to benefit the most from future optimization, though that is outside the scope of this paper. With the current algorithm, a standard desktop computer can keep up with ~ 8 pixels being sampled at 10^4 Hz in real time.

4 Results

This technique is capable of recovering piled-up pulses separated by as little as a rise-time with the same spectral resolution achieved for non-pile-up events. Fig. 4 shows this technique applied to calibration data taken on the launch rail with our XQC sounding rocket payload. For comparison, the measured FWHM of the oxygen $K\alpha$ line (525 eV) is 11.36

± 0.23 eV for non-piled-up pulses (i.e., pulses separated by more than 200 ms), and 11.27 ± 0.22 eV for piled-up pulses. XQC features an ion-implanted silicon thermistor microcalorimeter array with mercury telluride absorbers optimized for detecting soft X-ray photons below 1 keV [3]. Utilizing this technique, we are able to recover three times more pulses from our calibration data, with similar improvements expected for the observation. Pulse separations comparable to the thermal decay time of the detectors ($\tau = 9$ ms for XQC) result in decreased gain for the second pulse due to the higher starting temperature and intrinsic non-linearity of the detectors (Fig. 5). This can be fully corrected with an empirically created look-up table if the shape of the pulse is not significantly changed [2]. Substantial changes in shape with energy would result in some degradation in resolution, however this is true even for conventional optimal filtering techniques. In the regime where pulse shape is changing significantly, the assumption of stationary noise breaks down and different techniques are needed for optimization [4].

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Fig. 1. Piled-up pulses in XQC calibration data. All seven pulses in this data segment have a minimum separation of less than the 200 ms filter length typically used for this detector, and therefore cannot be processed using conventional optimal filtering techniques. Using the techniques presented here, however, each of these pulses may be recovered without loss of spectral resolution.

Fig. 2.

Top Left: Average signal shape constructed from 35 isolated calibration pulses prior to filtering (normalized to unity amplitude). *Bottom Left:* Isolated pulse that has been optimally filtered for pulse amplitude. *Bottom Right:* Isolated pulse that has been optimally filtered for pulse arrival time. These serve as templates for fitting pulses in the filtered data streams

Fig. 3.

Data segment from Fig. 1 after optimal filtering for pulse amplitude (*left*) and pulse arrival time (*right*). Open circles represent the fit to the data at the pulse arrival times. Residuals shown are the difference between data and the model at all times, illustrating the success of this model in fitting the data, even at times not considered in the fit.

Fig. 4. Scatter plot of the measured X-ray energy from a multi-line fluorescent calibration source, where the time shown for each point is the separation from a large pulse (~ 3 keV) at $t = 0$. None of the events shown could be processed with conventional techniques using the standard 200 ms filter for this detector. Measurement of the line widths as a function of pulse separation reveal no detectable broadening for separations as small as one rise-time (1.5 ms for these detectors).

Fig. 5.

Magnification of the 3.3 keV K K_{α} line from Fig. 4. The gain is low for events occurring while the pixel is still cooling from the preceding event, but this is easily corrected without loss of resolution, provided the pulse shape is not changing significantly as a function of energy.