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Digital signal processing algorithms for energy dispersive x-rays detectors

To cite this article: Sarmad Adeel and Martin Tolkiehn 2022 *J. Phys.: Conf. Ser.* **2380** 012098

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Abstract. Alternative to the traditional analog methods, several digital data preprocessing, shaping and postprocessing techniques have been investigated for the improvement in energy resolution of energy dispersive x-rays detectors. Initial experimental results show that by preprocessing the data, better energy resolution can be obtained at shorter shaping times; thus, it will allow good energy and time resolution at high count rates.

1. Introduction

In the field of energy dispersive x-rays detectors traditional analog signal processing involves a preamplifier to amplify the signal, a shaping amplifier to detect the energy of the incident photon, and a Multichannel Analyzer (MCA) to generate the energy spectrum. The use of digital signal processing allows to enhance the system, achieve more flexibility, reduce noise by adding advanced digital and faster data processing methods, which will enable higher counting rates above million counts per second. With digital signal processing the output of the preamplifier is digitized, and all further processing is done in a Field Programmable Gate Array (FPGA) as shown in figure 1. Currently available devices in the market perform the signal processing step either in Digital Signal Processors (DSPs) or FPGAs at expense of large shaping times. Some devices even use additional analog signal processing step.

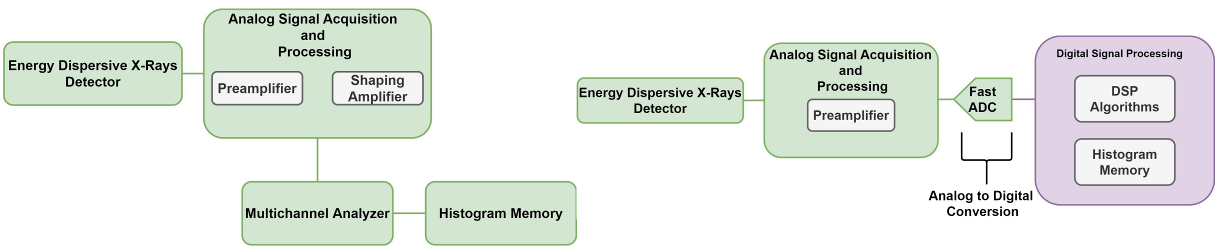

Figure 1. Analog and Digital Signal processing in Energy Dispersive X-Rays Detectors.

This paper will investigate different methods for data preprocessing, shaping and postprocessing. This paper will demonstrate that by preprocessing the data, good energy and time resolution at high count rates can be obtained.

Signal preprocessing methods such as moving average, Savitzky-Golay and Gaussian filter will be shown. For signal shaping we will show methods such as trapezoidal, and triangular filter. To avoid signal pileup issues, postprocessing methods such as deconvolution will also be demonstrated. The results of the methods will be compared by applying them to identical experimental raw data. Based on theoretical and experimental results an analytical comparison of the methods will be carried out for the implementation.

2. Methods

The very first step involved in the pulse height extraction is to correct the baseline. After baseline correction, the noise in the signal needs to be removed. To remove noise and increase the signal quality signal preprocessing methods are applied. The signal is then shaped to extract the pulse height which is proportional to the energy of the photon deposited. In some cases when the count rate is high, two signals overlap with each other called pulse pileup. The pileup reduces the energy resolution and the count rate. To correct the pileup issue, the signal is passed to the postprocessing phase where multiple methods are applied to correct the pileup and extract the exact pulse height. The methods investigated are summarized in table 1.

Table 1. Methods investigated for energy dispersive x-rays detectors.

Signal Preprocessing	Signal Shaping	Signal Postprocessing
Moving Average Filter	Trapezoidal Shaping	Deconvolution
Savitzky-Golay Filter	Triangular Shaping	Fitting Methods
Gaussian Filter	Gaussian Shaping	Linear Predictive Coding

2.1. Signal Preprocessing

To filter out the noise in the signal, different methods are investigated. The simplest of them is the moving average filter. This filter, as the name suggests, takes a window size number of samples from the input signal to generate each point in the output signal [1]. Such a filter can be mathematically represented as equation 1.

$$y[n] = h[n] * x[n], \qquad y[n] \ = \sum_{k=0}^{N-1} h[k] \cdot x[n-k] \tag{1}$$

Where x[n] is the input signal, y[n] is the output signal, h[n] is the impulse response, n is the number of sample and N is the size of the filter. Moving average filter coefficients are always $\frac{1}{N}$, hence has rectangular impulse response h[k].

Savitzky-Golay is a smoothing filter which takes a window size number of samples, fits a lower order polynomial to the samples in the window size to produce single output with corresponding value of the fitted polynomial. Thus it is also called polynomial or least square filter. The former two filters can be differentiated by degree of polynomial. Zero order Savitzky-Golay filter becomes moving average. Savitzky-Golay preserve data peaks, heights or in other words data features because of higher degree polynomial while moving average usually attenuates such features [2].

When the impulse response h[k] is Gaussian, the filter is acting as a low pass and it is called Gaussian smoothing filter. The Gaussian can be represented as $G(x) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left(-\frac{x^2}{2\sigma^2}\right)$ [1], where x is the input signal, σ is standard deviation.

2.2. Signal Shaping

To shape the signal to extract the precise pulse height signal shaping methods are used. One of the most used shaping methods for energy dispersive x-rays detectors is called trapezoidal shaping filter, where the input signal is shaped like a trapezoid with specific peaking time, gap time. The advantage is good energy resolution at expense of large shaping time. Due to large shaping time, in cases of high count rates, pulse pileup issue hinders its performance [3]. To solve the large shaping time issue of trapezoidal shaping, triangular filter is used. The triangular shaping has advantage of zero gap time (flat top) which increases the performance of this method in high count rates, but it requires signals with short rise time otherwise it will lead to degradation of energy resolution [3]. Alternative method is Gaussian shaping where the signal is shaped like a Gaussian at expense of larger shaping time than previous signal shaping methods.

2.3. Signal Postprocessing

Signal postprocessing is divided further into two types of methods, treating pileup issues before spectrum generation (i.e., recover each pulse from pileup), which is also called single event reconstruction, and treating pileup issues after spectrum generation (i.e., treating the spectrum to remove the effects of pileup). This paper is focused on single event reconstruction methods for real time implementation. Correction of pileup issues after spectrum generation is more hardware expensive and hence it can be implemented in software. The methods investigated are Deconvolution, Fitting Methods and Linear Predictive Coding (LPC).

3. Hardware

The hardware board used for experimental verification is SIS8300KU from Struck Innovative Systeme GmbH. SIS8300KU is a 10 channel 125 MS/s digitizer with 16-bit resolution. It comes with Xilinx Kintex Ultrascale FPGA, Advanced Mezzanine Card (AMC), Micro Telecommunications Computing Architecture (MTCA) standard for physics board, 4 Lane Peripheral Component Interconnect Express (PCIe) Gen3 interface [4]. The Rear Transition Module (RTM) used is called SIS8900 from Struck [5]. The SIS8900 is a 10 channel single ended input RTM according to the MTCA.4 standard. It has 10 channels with either Alternative Current (AC) and Direct Current (DC) options. For this experiment, DC inputs with +/-2.5V range and 1kΩ impedance was used.
The data is acquired at Chemical Crystallography beamline P24 at PETRA III. The experimental setup consist of ultra high performance Silicon Drift Detector (SDD) from AMPTEK [6]. The output from detector is connected to PA-210 preamplifier also from AMPTEK [7]. The output of the preamplifier is then connected to the RTM SIS8900. The RTM is connected to the SIS8300KU through Zone 3 connection. The block diagram of the hardware setup is shown in the figure 2. All digital processing is then being performed on the SIS8300KU board. The application firmware is embedded in the MSK Firmware Framework from DESY Hamburg. A Qt based Graphical User Interface (GUI) based on Chimera TK is used for testing. C Code based environment is used for the data analysis, acquisition, testing and verification. It uses optimized driver that allows Direct Memory Access (DMA) transfers.

4. Results

Two different sources are used for two different experiments with the same setup. For industrial comparison a standard radioactive iron source (^{55}Fe) is used. Another experiment is performed on the material Yttrium Aluminum Garnet ($Y_3Al_5O_{12}$) which was radiated with 0.5 Å x-rays.

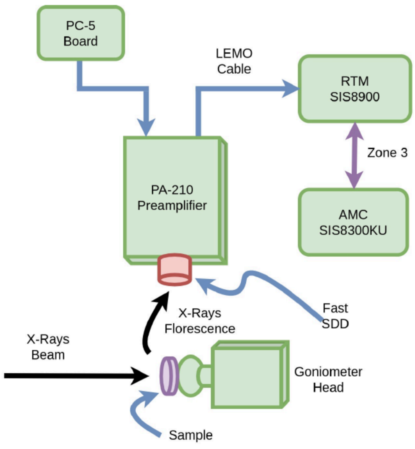

Figure 2. Hardware Setup.

4.1. Results from Iron Source

This source basically emits two lines: Manganese (Mn) Kα and Mn Kβ. The iron decays by electron capture to Mn. The first energy line Mn Kα is at 5.9 keV while the second energy line Mn Kβ is at 6.5 keV [8]. The input raw Analog to Digital Converter (ADC) data with a photon strike is collected from the detector as shown in the figure 3. After histogram generation and energy calibration, then the energy resolution is determined by calculating the Full Width Half Maximum (FWHM) in electron volts (eV) of the two Mn lines is recorded by using fitting methods as shown in the figure 4. On the x-axis are the methods that were applied to the

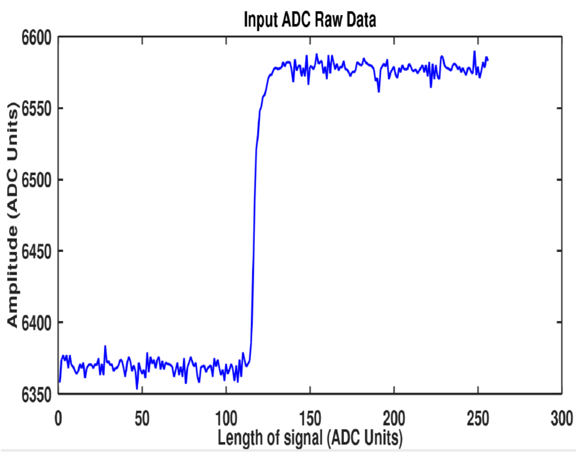

Figure 3. ADC Data for a single photon.

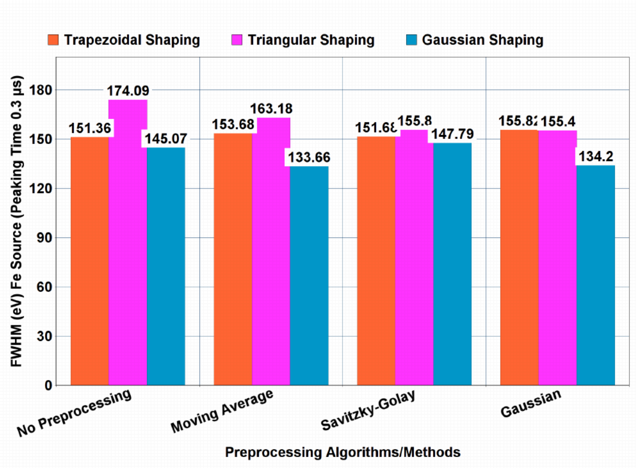

Figure 4. Results of several digital signal processing methods.

data. The y-axis represents the FWHM in electron volts (eV). The first bar shows FWHM for trapezoidal shaping, the second bar shows the triangular while the last bar shows the FWHM for Gaussian shaping. The peaking time of the trapezoidal and triangular method is set to 0.3 μs, while Gaussian shaping is set to 1.0 μs. The flat top of the trapezoidal shaping is set to 0.1 μs.

When no preprocessing is applied to the shaping methods, the trapezoidal shaping method gives good energy resolution around 150 eV at expense of 0.7 μs shaping time (2 $\times$ peaking time + gap time). The triangular shaping gives around 175 eV but 0.6 μs shaping time as there is no flat top. The Gaussian shaping is giving better energy resolution than the prior two methods at

expense of 1.0 μs shaping time. When preprocessing moving average filter is applied, it improves the energy resolution for triangular shaping methods roughly to 160 eV and Gaussian shaping to 130 eV. Preprocessing Savitzky-Golay method improves the energy resolution of the triangular shaping to around 150 eV. Thus at 0.6 μs shaping time triangular shaping with Savitzky-Golay method roughly gave the same energy resolution as the trapezoidal shaping.
On the other hand Gaussian preprocessing method degrades the energy resolution for trapezoidal shaping but improves the energy resolution for triangular and Gaussian shaping.

4.2. Pileup Analysis for iron Source

To analyze and improve count rates in case of pileup events, several postprocessing methods are analyzed. A pileup event recorded from iron source is shown in the figure 5. Now a trapezoidal shaping was applied in this case which totally ignores the next photon due to larger shaping time. Then with the postprocessing method both photons are counted thus allowing for higher count rates in this case as shown in the figure 6.

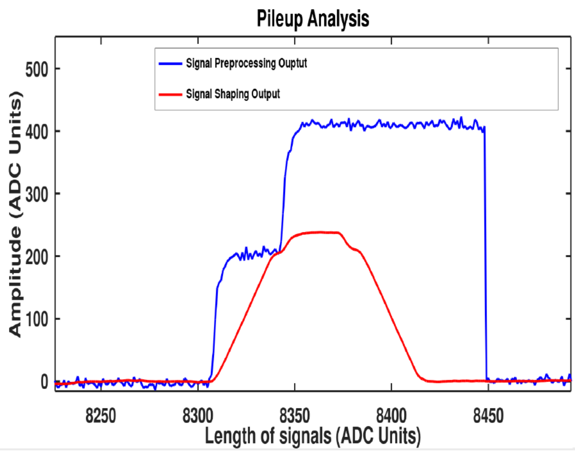

Figure 5. Two photons as single trapezoid

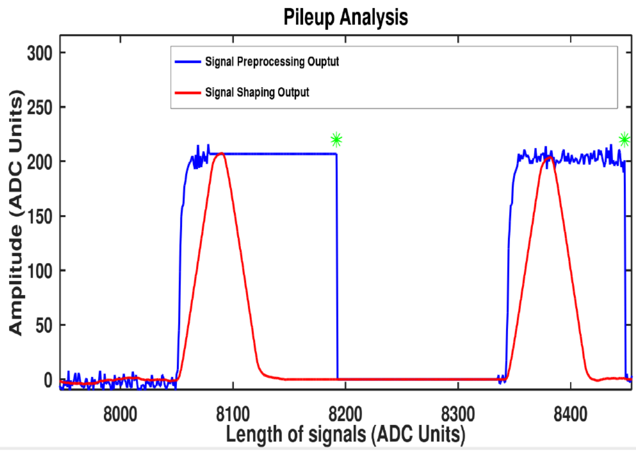

Figure 6. Two photons as two trapezoids

4.3. Results for Yttrium Aluminum Garnet

This source emits two lines: yttrium Kα and Kβ. The first energy line yttrium Kα is at 14.9584 keV while the second energy line yttrium Kβ is at 16.7378 keV [8]. The raw ADC data with a photon strike is collected from the detector as shown in the figure 7. After histogram generation and energy calibration, the energy resolution is determined by calculating the Full Width Half Maximum (FWHM) in electron volts (eV) of the two yttrium lines is recorded by using fitting methods as shown in the figure 8. The x-axis shows the methods that were applied to the data. The y-axis represents the FWHM in eVs. The first bar shows FWHM for trapezoidal, the second bar shows the FWHM for triangular shaping. The peaking time of the trapezoidal and triangular method is set to 0.2 μs. The flat top of the trapezoidal shaping is set to 0.1 μs.
When no preprocessing is applied to the shaping methods, the trapezoidal shaping method gives good energy resolution around 170 eV at expense of 0.5 μs shaping time. The triangular shaping gives around 220 eV but 0.4 μs shaping time as there is no flat top. Moving average improves the energy resolution for both shaping methods roughly to 140 eV for trapezoidal while triangular shaping to 178 eV. Savitzky-Golay hardly improves the energy resolution for the trapezoidal but it improves the energy resolution of the triangular shaping to around 175 eV. Thus at 0.4 μs shaping time triangular shaping with Savitzky-Golay method gave better energy resolution

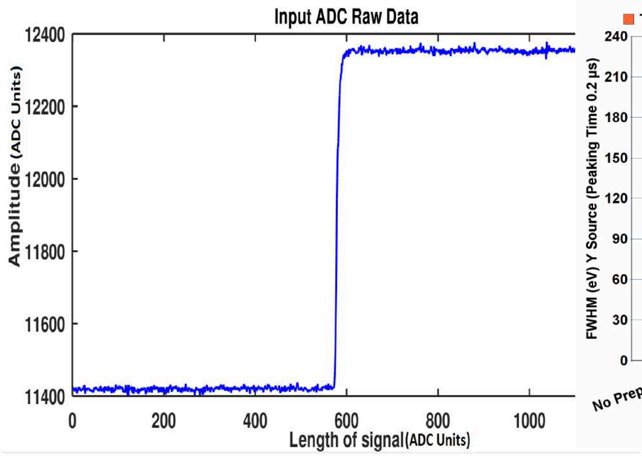

Figure 7. ADC Data for a single photon.

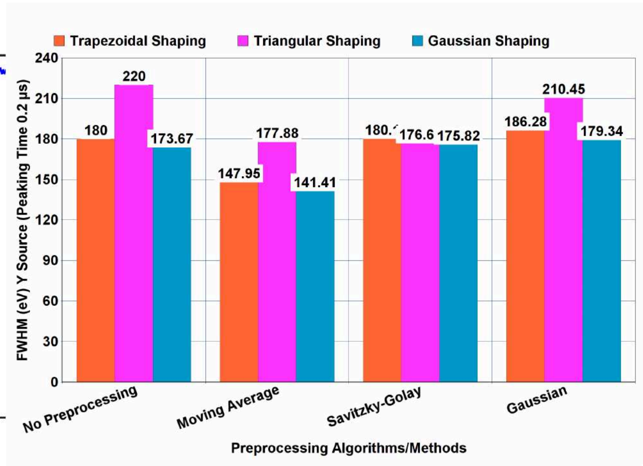

Figure 8. Results of several digital signal processing methods.

than the trapezoidal shaping. While Gaussian preprocessing degrades the energy resolution for trapezoidal and Gaussian shaping but improves the energy resolution for triangular shaping.

5. Conclusion

Several digital signal processing methods have been analyzed to not only improve the energy resolution but also the arrival time of photon for energy dispersive x-rays detectors. To conclude traditional analog signal processing has been shifted to digital domain. Digital domain provides the advantages of high flexibility, accuracy and more control over signal processing. Savitzky-Golay preprocessing enhanced the energy resolution of triangular shaping to 155 eV in case of iron source which is roughly closer or equivalent to trapezoidal shaping of 0.7 μs shaping time. In case of yttrium aluminum garnet Savitzky-Golay also enhanced the energy resolution of triangular shaping to 176 eV at expense of 0.4 μs shaping time. Thus, with preprocessing the data energy resolution can be improved at shorter shaping times. Signal postprocessing increases the photon counts. Moreover real time data analysis is provided.

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