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Evaluation of real-time digital pulse shapers with various HPGe and silicon radiation detectors

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ABSTRACT

Real-time digital pulse shaping techniques allow synthesis of pulse shapes that have been difficult to realize using the traditional analog methods. Using real-time digital shapers, triangular/trapezoidal filters can be synthesized in real time. These filters exhibit digital control on the rise time, fall time, and flat-top of the trapezoidal shape. Thus, the trapezoidal shape can be adjusted for optimum performance at different distributions of the series and parallel noise. The trapezoidal weighting function (WF) represents the optimum time-limited pulse shape when only parallel and series noises are present in the detector system. In the presence of $1/F$ noise, the optimum WF changes depending on the $1/F$ noise contribution. In this paper, we report on the results of the evaluation of new filter types for processing signals from CANBERRA high purity germanium (HPGe) and passivated, implanted, planar silicon (PIPS) detectors. The objective of the evaluation is to determine improvements in performance over the current trapezoidal (digital) filter. The evaluation is performed using a customized CANBERRA digital signal processing unit that is fitted with new FPGA designs and any required firmware modifications to support operation of the new filters. The evaluated filters include the Cusp, one-over-F ($1/F$), and pseudo-Gaussian filters. The results are compared with the CANBERRA trapezoidal shaper.

1. Introduction

The role of nuclear pulse processing hardware is to deliver the optimum resolution and throughput for a given detector system in a manner the user can readily analyze and interpret. Several factors dictate the appropriate data acquisition and analysis hardware needed for the best performance. Count rates spanning several orders of magnitude, transient count rates, different detector and preamplifier modalities, the range of gamma-ray energies of interest, dynamic environmental conditions such as temperature: these are all factors that must be taken into account when choosing an appropriate digital spectrum analyzer (DSA) for a gamma spectroscopy system. Digital signal processors (DSP) have recently been favored over analog electronics for spectroscopy systems due to their superior environmental, count rate stability, and processing flexibility. The performance of such systems is commonly quantified by energy resolution, stability and throughput. The total full width half maximum (FWHM) energy resolution W_T of a semiconductor detector depends upon a combination of three factors: the statistical distribution in the number of charge carriers W_D, variations in the charge collection efficiency W_X, and electronic noise W_E [1–2]. These three parameters add in quadrature: $W_T^2 = W_D^2 + W_X^2 + W_E^2$ .The parameter $W_D^2 = F\varepsilon E$ is directly proportional to the energy E deposited by the gamma-ray and to the electron-hole excitation energy ε of the semiconductor material (with a typical Fano factor $F = 0.11$ for Ge). W_X^2 depends on the detector volume, shape and the intensity of the electric field inside the crystal. Electronic noise is a contributing factor to energy resolution in semiconductor radiation detectors. It has been well described in the Ref. [3] and is thought to come from only a few different sources. These sources are the following: (1) the shot noise or the parallel thermal noise due to the detector leakage current, (2) the series thermal noise generated within the channel of the input JFET in the preamplifier due to the total input capacitance (of detector and FET), and (3) the $1/F$ noise generated in the detector itself. The total electronic noise is the quadratic sum of these separate components. In order to reduce the total electronic noise component, the signal from the preamplifier is shaped with characteristic parameters, such as the width or shaping time. The behavior of the various noise contributions as a function of shaping time varies depending on the noise source. The series noise deceases as the shaping time increase while the parallel noise behaves the opposite. The $1/F$ noise though, is independent of the shaping time. Lower shaping times are favored for high rate application where throughput is desired over resolution while larger shaping times are typically desired for

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low rate situation. The best operating values of shaping characteristic parameters depend on each application. In other words there could be several optimal case scenarios depending on the tradeoff between the minimization of resolution and throughput maximization. The trapezoidal digital shaper is a good example that handles well this tradeoff. However, in situations where throughput maximization is not a priority (such as low rate applications) and/or $1/F$ noise is a major noise component, there are other filters that could yield better energy resolution performance.

2. Real-time digital filters

Noise can be defined as an unwanted signal that obscures the desired signal. It can be thought of a random fluctuation of the signal in electronics circuits and amplifiers. The primary efforts in fabricating a semiconductor detector should be directed towards the minimization of the series, parallel, and $1/F$ noise contributions as much as possible. Shaping techniques are intended to improve the signal to noise ratio. Real-time digital pulse shaping techniques allow synthesis of pulse shapes that have been difficult to realize using the traditional analog methods. Using real-time digital shapers, triangular/trapezoidal filters can be synthesized in real time, as described in Ref. [5], or in quasi real time, as described in Ref. [6]. These filters exhibit digital control on the rise time, fall time, and flat-top of the trapezoidal shape. Thus, the trapezoidal shape can be adjusted for optimum performance at different distributions of the series and parallel noise. The trapezoidal weighting function (WF) represents the optimum time-limited pulse shape when only parallel and series noises are present in the detector system [3,7–9]. In the presence of $1/F$ noise, the optimum WF changes depending on the $1/F$ noise contribution. Optimum pulse shapes have been derived, as described in Ref. [10] for both cases of $1/F$ voltage and $1/F$ current noise sources. In this work, we considered new filter types (see Fig. 1) for processing signals from HPGe and PIPS detectors. The objective of the evaluation is to determine improvements in performance over the current trapezoidal (digital) filter. Two parameters are available to control the each of the filters: rise-time (sometimes referred to as integration time) and flat-top (Sometimes referred to as charge collection time). The rise-time is defined as the times it takes for the shaped signal to go from baseline to the start of the flat-top and the flat-top time is the “wait” time after reaching the flat region.

3. Experimental and results

The evaluation is performed using a customized CANBERRA digital signal processing unit (LYNX) [4] that is fitted with new FPGA designs and any required firmware modifications to support operation of the new filters. The evaluated filters include the cusp, $1/F$ and pseudo-Gaussian filters. The results are compared with the CANBERRA trapezoidal shaper. A set of detector types is chosen to perform the testing. The choice of detector types was dictated by the expected effect of the filters on the detectors and their availability at the time of the testing. The following CANBERRA detector types were considered: BE3820 BEGe: broad energy Ge detectors (LN2 cooled) [2,4], 30% relative efficiency medium coaxial detector GC3020 (LN2 cooled) [2,4], X-PIPS silicon detector (Peltier cooled) [2,4], GL1015S LEGe: low energy germanium detector (Canberra cryo-cycle cryostat: redundant electric/LN2 cooling) [2,4] and 52.6% relative efficiency GR5020 REGe: medium reverse electrode coaxial detector (LN2 cooled) [2,4]. FWHM resolution measurements were performed using Fe-55, Co-57, and Co-60 sources for the various digital filters by varying the rise-time. For each detector, the optimum flat-top is determined based on the trapezoidal filters, and that same value is used for the rest of the filters. The resolution measurements results are shown in Fig. 2 for the REGe, BEGe, and X-PIPS detectors. The dead-time was approximately 5% with 8.8 μs rise-time and 1.2 μs flat-top for the REGe, 8 μs rise-time and 1.2 μs flat-top for the BEGe and 20 μs rise time and 0.2 μs flat-top for the X-PIPS detector. Fig. 2(a) suggests that, for short rise-times, the trapezoidal filter results in better energy resolutions followed by the $1/F$ and cusp filters. The pseudo-gaussian shape gives the worst resolution for almost all the shaping times. We also notice that for larger shaping times the trapezoidal and pseudo-gaussian shapes tend to converge. The same can be concluded for the $1/F$ and cusp filters too at those large shaping times.

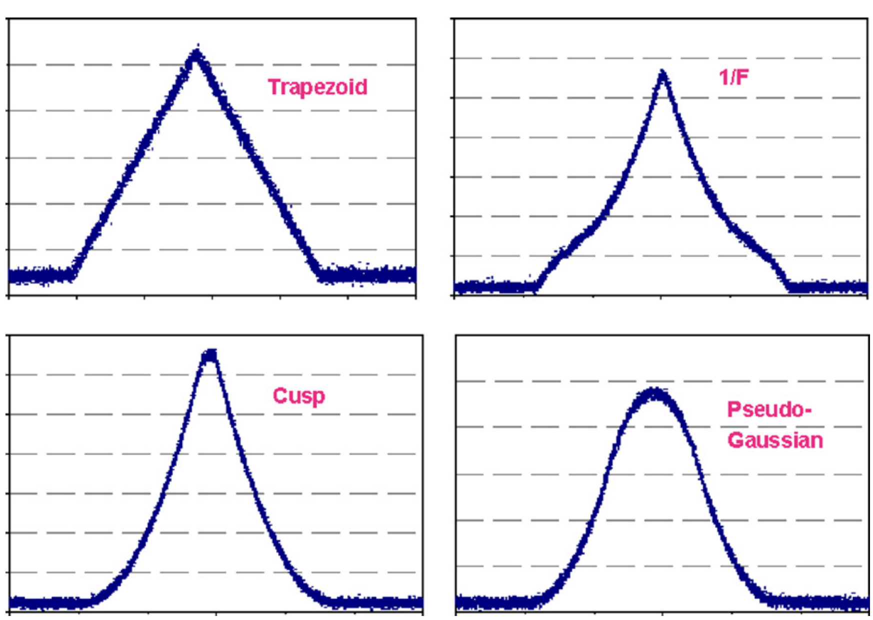

Fig. 1. Actual shaper traces for the trapezoidal, 1/f, cusp, and pseudo-Gaussian filters using a germanium detector. The flat-tops for all the filters was set to a very small value for visualization purposes only.

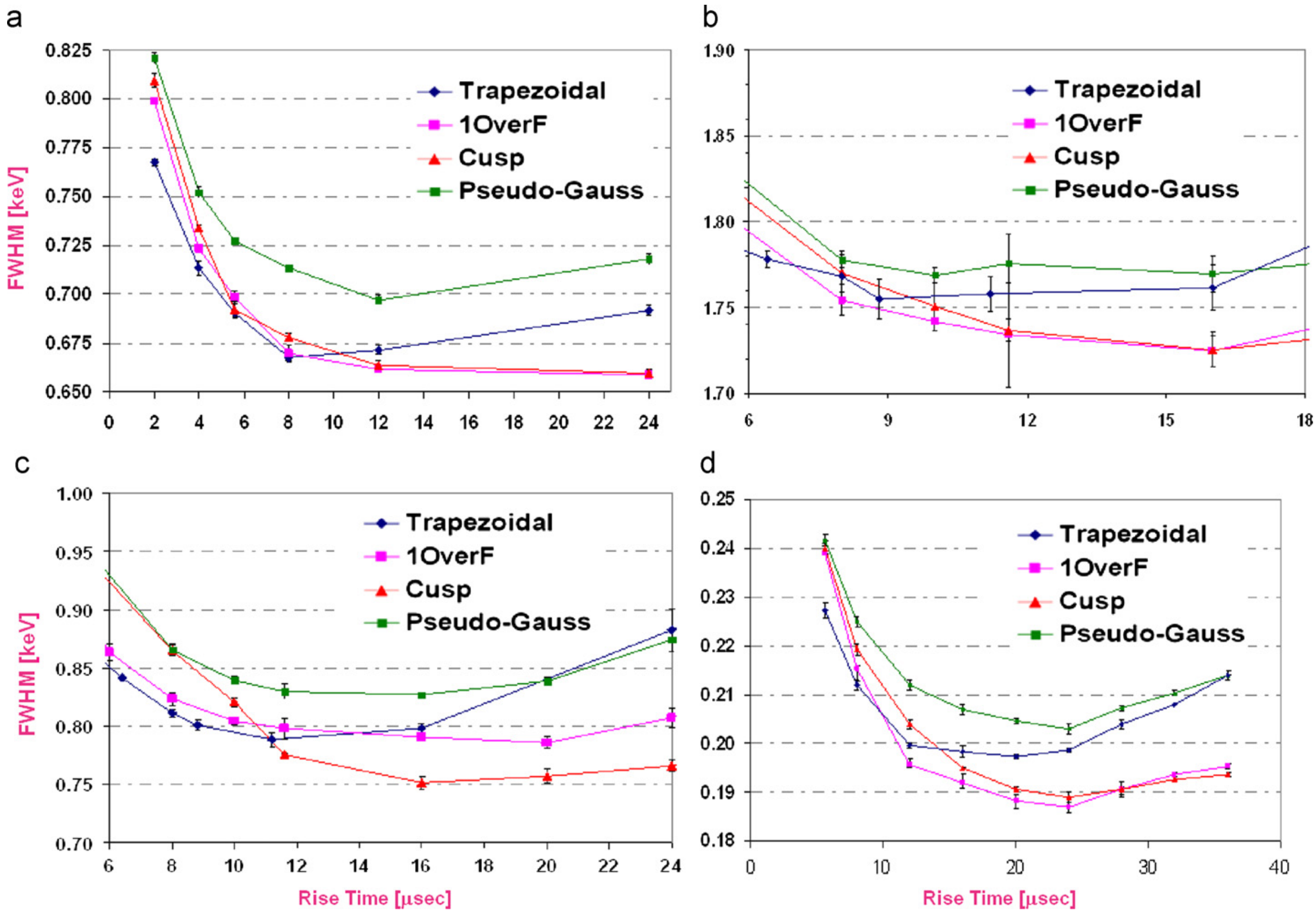

Fig. 2. Energy resolution measurements as a function of the rise time. (a) REGe detector at 122 keV, (b) REGe at 1332 keV, (c) BEGe at 122 keV, and (d) X-PIPS at 5.9 keV. The 1-sigma uncertainties shown on the data points are extracted using repeat measurements of the same point and taking the standard error of the mean.

Finally, one can conclude that for the REGe and BEGe detectors the cusp filter type is best for low noise germanium applications where the system noise is comprised of mainly series (voltage) and parallel (current) white noises sources and the application allows the use of longer shaping times if allowed by throughput requirement. One can also point out that for the X-PIPS, the $1/F$ filter type is valuable for silicon X-ray applications where the $1/F$ noise is a significant contributor to the total noise. This situation usually occurs when long shaping times are used to limit contribution from the series (voltage) noise sources and the parallel (current) noise sources are not significant at this shaping. The medium coax detector showed similar trends as the REGe detector and the LEGe results were also comparable to the BEGe conclusions.

4. Conclusions

Several types of filters were tested and proved to be able to affect the energy resolution and count rate performance of systems. From this study we conclude that the Trapezoidal filter is adequate for best energy resolution and high throughput general application. The cusp filter type is best for low noise germanium applications where the system noise is comprised of mainly series (voltage) and parallel (current) white noises sources. The noise is typically dominated by the electronic (thermal and shot) noise of the preamplifier FET with little flicker ($1/F$) noise present. The $1/F$ filter type is valuable for silicon X-ray applications where the $1/F$ noise is a significant contributor to the total noise. This situation usually occurs when long shaping times are used to limit contribution from the series (voltage) noise sources and the parallel (current) noise sources are not significant at this shaping. The pseudo-Gaussian filter is useful in applications where throughput is not an issue and time constants can be short. Since the signal to noise (S/N) ratio is not as good as the trapezoid filter under typical noise conditions the main value of this filter is the appeal to spectroscopy users that are still using analog signal conditioning methods. The user should get comparable results to the old analog systems but with much better temperature stability and better repeatability. These shapers are serious candidates for field usage and while one might be advantageous under some noise, charge collection and rate circumstances another might be preferred under different conditions. A good reference point must involve primarily a trade-off between energy resolution and signal throughput at high counting rate. The presented filters are impractical to implement using analog electronics hence the need for digital signal processing which allows great flexibility and the ability to maintain high signal fidelity almost indefinitely.

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