Improved Performance in Germanium Detector Gamma Spectrometers based on Digital Signal Processing

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INTRODUCTION

Digital Signal Processing (DSP) techniques have been used in the field of HPGe detector gamma-ray spectrometry for some time. In principle, digital systems offer improved stability and performance over their analog counterparts. Recent developments in HPGe detector construction, and new liquid nitrogen-free cooling methods have resulted in HPGe detectors which are better adapted to the needs of the application rather than merely meeting a nominal specification such as the IEEE-defined relative efficiency. With DSP, it is possible to enhance, in real time, several aspects of detector performance on a pulse-by-pulse basis, which is not possible in the old analog environment.

A DSP system replaces the familiar shaping amplifier and correction circuits, and ADC with a single digital system that processes the sampled waveform from the preamplifier with a variety of mathematical algorithms. In the past, designing for the analog regime, the flexibility was limited by issues of component size, number and cost. In the digital domain, the problem translates to the need for a DSP with enough speed and an efficient enough algorithm to achieve the desired transformation or correction to the digitally determined pulse height, event by event.

The use of DSP allows the peak processing to be adapted or tuned much more precisely to the preamplifier peak shape from the detector rather than being set to an average value determined from several detectors of the type in question. The adaptation of the filter can be automatic or manual.

Analog amplifiers used a limited number of different filter shapes to shape the preamplifier output for subsequent processing by the ADC. DSP units usually have trapezoidal filters with the shape adjustable in several ways, but with a wider range and finer steps than analog units. The adjustments in a simple system are the risetime, falltime, width of the flattop and the tilt (angle with the baseline) of the flattop. The risetime and falltime correspond to the shaping time constant in an analog filter. The flattop can be used to compensate for ballistic deficit, thus improving peak resolution and shape, especially in large coaxial detectors. Charge trapping occurs in all HPGe detectors. In the absence of trapping (and ballistic deficit) all detectors having a typical noise of about 0.5 keV would have an energy resolution at 1.33 MeV of about 1.6 keV FWHM and would have perfect peak shape. For some detectors there is a correlation between the risetime of the preamplifier pulse and the amount of trapping. In this case the energy resolution and peak shape can be improved by appropriate signal processing.

Two sources of noise that can degrade spectrum peak resolution and shape are microphonic and electrical noise; examples being vibration-induced noise and ground loops, respectively. These noise sources are characterized by a relatively slowly (compared to the time of a peak pulse) varying baseline. Special digital filtering techniques have been developed to improve the peak resolution in detectors with noise of these types.

Maximum achievable throughput and system resolution are related to the filter width; in general, reducing the filter width increases throughput, but worsens the resolution, mainly due to the series noise contribution to the total noise. Conventional systems require that the pulse from the digital filter completely return to the baseline before a subsequent pulse can be recognized. This requirement is convenient, but not necessary. With proper design of the pile-up rejector and peak detector, pulses closer in time can be analyzed, thus improving the system throughput. Accepting a pulse occurring very close to a preceding pulse can result in a loss of energy resolution. The minimum time interval ("protection time") can be adjusted to achieve an optimum tradeoff between throughput and resolution.

In some analog high-count rate spectrometers, so-called "loss free" counting techniques have permitted accurate dead time correction in cases where the input count rate is varying rapidly. Calculation of the uncertainty on these measurements, however has not proved possible until a digital implementation was made, which allows the pulse-by-pulse collection of not only the corrected primary energy spectrum, but also the corresponding variance spectrum, thus permitting accurate uncertainty determination.

DIGITAL FILTER

The general shape of the digital filter is shown in Fig.1. The Risetime and Falltime are equal. While the cusp is predicted by theory, current DSP filters are generally simple trapezoids. [1] The risetime is adjusted for the minimum noise unless the count rate is high enough to cause significant pileup losses. Shorter risetimes may then be used to achieve higher throughput with somewhat higher noise. If the flattop is adjusted to a value longer than the longest detector charge collection time, ballistic deficit effects can be essentially eliminated.

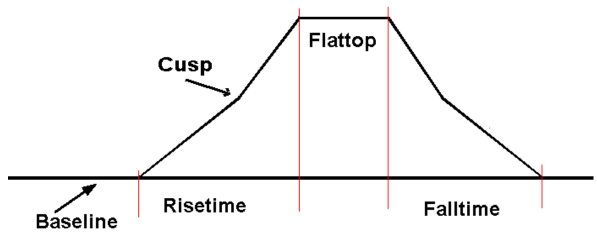

Fig. 1. A general DSP filter shape.

GERMANIUM DETECTORS

Ballistic Deficit

The amplifier output pulse height is related to the charge collected for the integration time of the amplifier. Fig. 2 shows two pulses; one where the total charge was collected in a very short time (zero), and one where the charge collection took a long time. If the amplifier time constant was longer than the collection time, the two output pulses would be the same. However, there is a practical limit to the time constant, so the output pulse amplitudes are different. The variation in charge collection can vary with the site of the gamma-ray interaction, so there will be a range of charge collection times. [2]

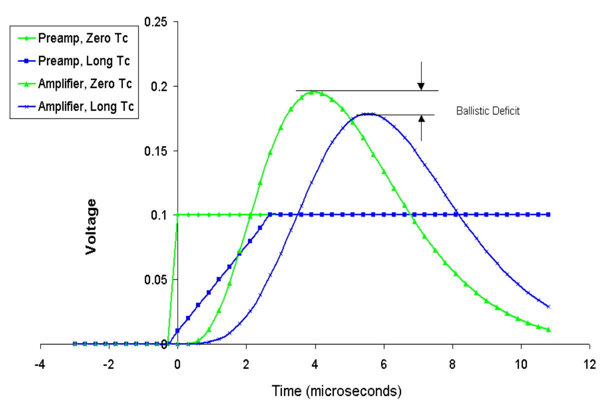

Fig. 2. Ballistic deficit effect on pulse height.

Ballistic deficit is the term used to describe the reduction in the recorded pulse height due to variations in the charge collection. If the system has ballistic deficit effects, variations in detector charge collection time will produce poor resolution and poor peak shape. Such effects are most common in larger detectors. Simply increasing the charge integration time to account for the longest collection times will increase the parallel noise contribution and reduce the throughput.

The flattop portion of the filter is used to compensate for the difference in amplitude with rise time. The peak amplitude is determined as the maximum point during the flattop time.

The flattop width can be adjusted to give the best tradeoff between throughput and resolution.

Charge Trapping

Charge trapping occurs when some of the electrons or holes from the interaction of the gamma ray with the detector do not drift to the contact in the expected time. [3] The traps in the crystal are due to impurities in the lattice or structural defects in the crystal. The charge may be delayed in reaching the contact or completely lost. The pulse amplitude is reduced when the charge is not collected completely during the integration time. The reduction varies with different pulses which causes the spectrum peak to broaden.

In addition to the delayed charge reducing the pulse amplitude, the delayed charge collection also delays the time when the pulse reaches its maximum. The peaking time (time between the beginning of the pulse and the maximum) is longer for the pulses with charge trapping. Each detector will have different characteristics due to the particular crystal. The resolution enhancer uses this characteristic to adjust the gain to compensate for the losses. In the setup phase, the rise time of the preamplifier output pulse is measured and recorded as a function of the peak amplitude for a particular spectrum peak. From this relationship, a correction factor (gain adjustment) is determined as a function of the rise time. In the data collection, the rise time is measured and the pulse amplitude is multiplied by the correction factor.

The determination of the correction factor is automated and must be redone if the detector is changed. Figures 3 and 4 show the improvement in the resolution. Note, in Fig. 4, that the number of counts in the maximum channel in the spectrum peak has increased, because the same number of counts are now included in a narrower peak.

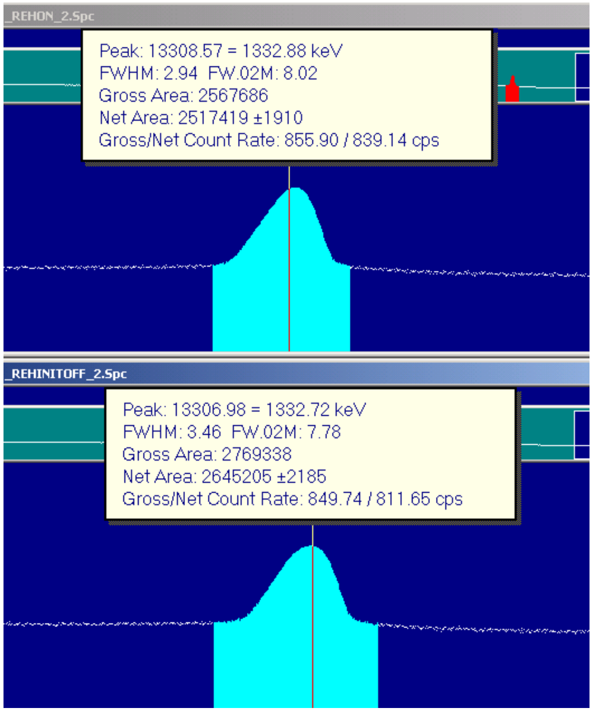

Fig. 3. Comparison of the peak resolution for enhancer on and off.

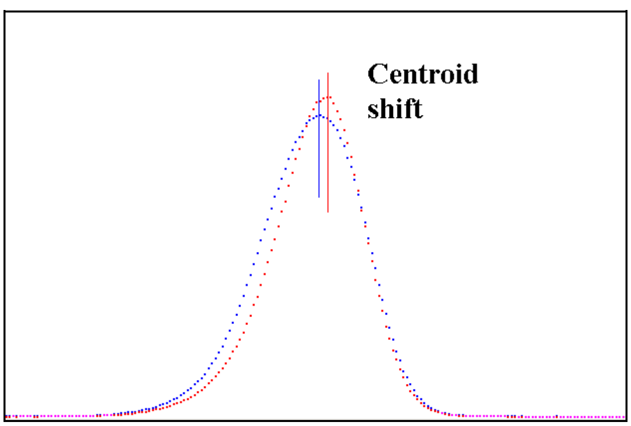

Fig. 4. Overlap comparison of the spectrum peaks in Fig. 3.

Low Frequency Noise Rejector (LFR)

The digital filter shown in Fig. 1 assumes that the peak baseline is the same on both sides of the pulse. [4] In the case of low frequency noise from detector microphonics or ground loops, this is not the case. When the interference has a much longer periodicity, the detector pulse is riding on the signal and the spectrum base is not constant before and after the pulse as shown in Fig. 5.

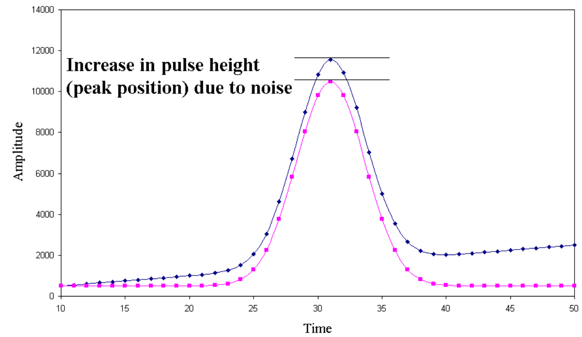

Fig. 5. Impact of noise on pulse height.

The DSP filter to remove the noise is shown in Fig. 6. The area of the central trapezoid is the sum of the two outer trapezoids.

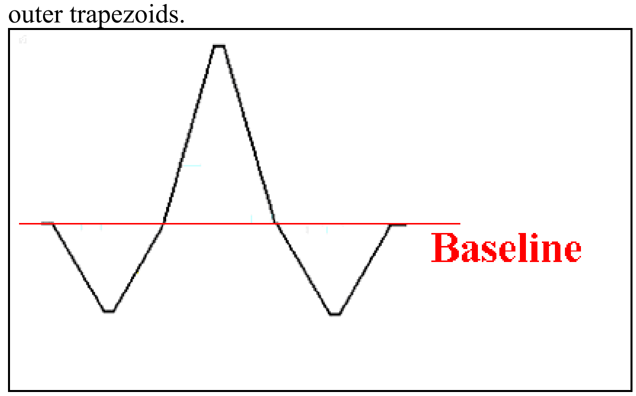

Fig. 6. The filter for low frequency rejection.

Fig. 7 shows the improvement in the resolution for the detector in the Detective, where the mechanical cooler introduces vibration.

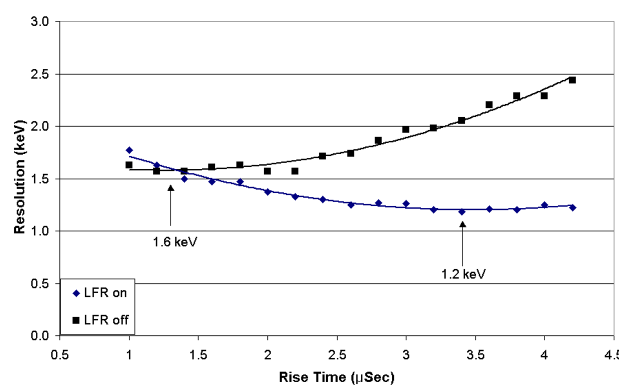

Fig. 7. Resolution at 59 keV with LFR on and off for the Detective mechanically-cooled detector.

Throughput Enhancement

The throughput of the system is determined by the total width of the filter as shown in Fig. 1. [5] The deadtime per pulse is the time from the beginning of the first pulse to the time the system can process a second, pileup free pulse. When the rise and fall times are equal, this is 3 times the risetime and two times the flattop as shown in Fig. 8.

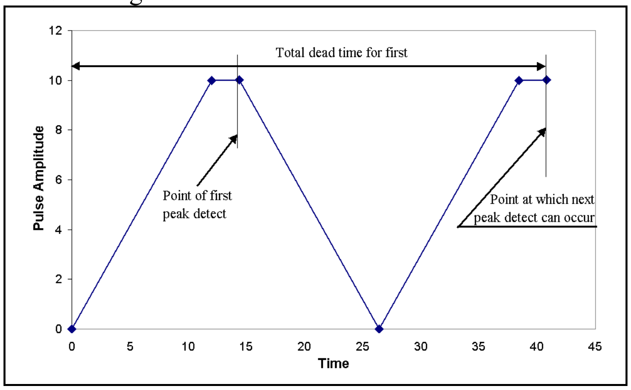

Fig. 8. Ideal pulse processing.

Figure 8 shows the non-LFR case. If the LFR is enabled, the dead time is increased by 3 times the width of the side lobes.

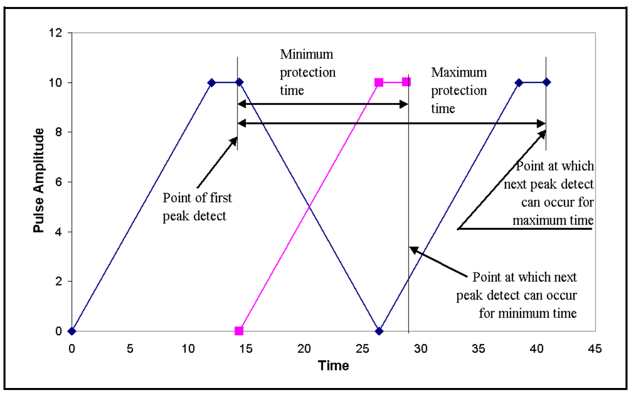

Fig. 9. Pulse processing with different protection times.

The dead time per pulse can be reduced by allowing the second pulse to be processed before the first pulse has completely returned to the baseline. The flat top region must be after the first pulse has returned to baseline. This is shown in Fig. 9.

If the first pulse does not return to the baseline before the end of the filter, the second pulse maximum will be increased and this will increase the spectrum resolution. The decrease in the peak processing time will increase the throughput. Figure 10 shows the increase in throughput of the DSPEC Pro in this mode compared to the predicted throughput. The DSPEC Pro has a maximum throughput of about 130000 cps.

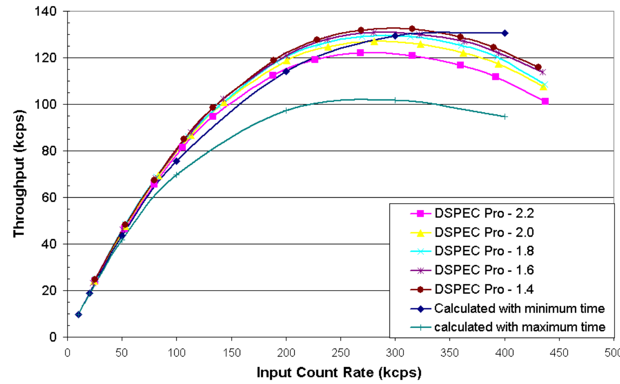

Fig. 10. DSPEC Pro throughput at different protection times compared to predicted value.

Zero Dead Time or Loss Free Counting

In cases where the count rate varies during the data collection time, the conventional extended live time correction mode, or “LTC method” does not correctly compensate for the counts lost during the system dead time. [6] This variation in count rate can be caused by short halflife nuclides or by changes in the sample, such as material flowing in a pipe. The live time correction mode extends the counting time to compensate for the lost counts, but if the gamma ray flux has changed, the added counts do not represent the counts lost during the dead time.

The Zero Dead Time (ZDT) corrects in real time by monitoring the system dead time at the time of the event and multiplying the individual counts by the ZDT correction factor. (For example at a constant 50% dead time, each event digitized would result in 2 events being added to memory.)This results in a spectrum collected with no dead time losses, but the uncertainty of each channel is no longer simply the square root of the channel contents. The uncertainty of the spectral data is important in determining the total uncertainty of the analysis results. The ZDT method also calculates the variance of the individual channel contents event by event, and this variance spectrum is stored with the data spectrum in the DSPEC Plus and Pro.

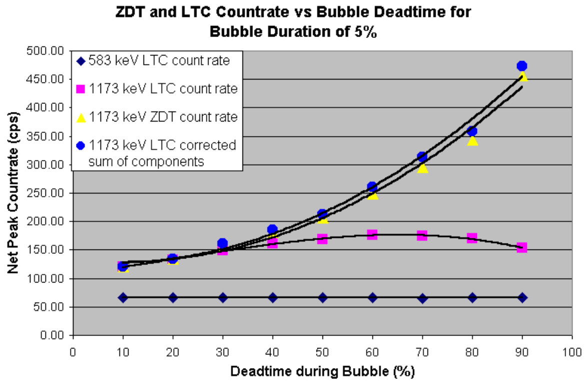

Fig. 11. ZDT and LTC count rate vs bubble deadtime for bubble duration of 5%.

Figure 13 compares the ZDT corrected results with the calculated results when the deadtime during the high activity time varies from 10% to 90%. The “corrected sum” data is the “right answer” for the 1173 keV peak in this example. The ZDT corrected data follows this curve closely, while the traditionally corrected LTC 1173 keV data is in serious error. The 583 keV data is corrected data taken at constant input count rate for this peak showing that the LTC method is accurate until the count rate for this peak is varying with time.

CONCLUSIONS

Improvements in DSP processors have made possible the introduction of several methods to improve gamma ray spectra in resolution, throughput, resistance to noise, and changing counting conditions. All of these conditions are experienced in data collection situations.

REFERENCES

1. R. D. Bingham, A Digital Filter for High-Purity Germanium Detector Spectrometry, Dissertation, University of Tennessee, 1996
2. F. S. Goulding and D. A. Landis, Ballistic Deficit Correction in Semiconductor Detectors, IEEE TNS, Vol 35, No 1, 1988, 119-124
3. M. L. Simpson, T. W. Raudorf, T. J. Paulus, and R. C. Trammell, Charge Trapping Correction in Ge Spectrometers, IEEE TNS, Vol. 36, No. 1, 1989, 260-266
4. R. M. Keyser and R. C. Trammell, Performance of an Enhanced Throughput Feature in a High-Count Rate System, IEEE NSS MIC 2004
5. R. M. Keyser, T. R. Twomey, and D. L. Upp Performance of Light-Weight, Battery-Operated, High Purity Germanium Detectors for Field Use, INMM 2003 Annual Meeting
6. R. M. Keyser, T. R. Twomey, and R. D. Bingham, Performance of the Zero-Dead-Time Mode of the DSPEC Plus, ANS 2001 Annual Meeting