THE USE OF WAVEFORM DIGITIZERS WITH SOLID STATE DETECTORS FOR SPECTROSCOPIC APPLICATIONS

by

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A senior thesis submitted to the faculty of

Brigham Young University

in partial fulfillment of the requirements for the degree of

Bachelor of Science

Department of Physics and Astronomy

Brigham Young University

April 2010

BRIGHAM YOUNG UNIVERSITY

DEPARTMENT APPROVAL

of a senior thesis submitted by

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This thesis has been reviewed by the research advisor, research coordinator, and department chair and has been found to be satisfactory.

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ABSTRACT

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Data acquisition systems used for spectroscopy have undergone many changes over the past several years. Rapid changes in both hardware and software cause these systems to become obsolete very quickly. A new technology known as waveform digitization has recently become available. In principle, waveform digitizers could replace several components of older data acquisition systems. In this study, waveform digitizers were applied to x-ray and gamma-ray spectroscopy. These results are compared to the older data acquisition systems. Waveform digitizers have been found to be useful; however, some problems need to be overcome before they are widely used. Waveform digitizers work well when the signal does not have to be processed through an amplifier, as the amplifier makes the signal too wide for the digitizer to process. The different preamplifiers used with solid state detectors present other problems for waveform digitizers. Once the initial challenge of obtaining a spectrum was

overcome, we set out to answer two questions: (a) Can waveform digitizers handle count rates typically encountered in spectroscopic applications? and (b) Can we obtain energy resolutions comparable with other data acquisition systems? We found that the waveform digitizer we used worked well at a rate of 20,000 counts per second, but that the resolution was not as good as expected. This problem with the preamplifier needs to be solved to make the digitizer suitable for spectroscopic applications.

ACKNOWLEDGMENTS

I would like to acknowledge and thank Dr. Lawrence Rees for his constant help and assistance throughout the whole project. Without him, none of this would have been possible. Thanks also to John Ellsworth who provided the digitizer and wonderful help with the XRF.

Contents

List of Figures

Chapter 1

Introduction

1.1 Introduction

Solid state detectors are used on a wide range of applications to detect both photons and charged particles. BYU employs solid state detectors for particle-induced x-ray emission spectroscopy, x-ray fluorescence spectroscopy and gamma-ray spectroscopy. Data acquisition systems go hand in hand with detectors. At BYU, we use data acquisition systems based on VAX computers and PCs enabled with ISA bus cards. These technologies are very old and outdated. My thesis is an investigation into the use of waveform digitizers as a way to replace the outdated technology. I found that waveform digitizers are promising in the area of both x-ray and gamma-ray detection, but challenges arise when trying to digitize the output from some preamplifiers.

1.2 Background

PIXE

Particle-induced x-ray emission (PIXE) spectroscopy is used for trace element

analysis of samples. It is a process by which a beam of charged particles from an accelerator is incident on a sample; at BYU we accelerate protons to 2.16 MeV with a van de Graaff accelerator. As the protons strike the target, electrons are ejected from atoms in the sample [1]. After these inner-shell electrons are knocked off from atoms, x-rays are emitted by the ionization of the atoms in the sample. The spectrum contains both background x-rays and the characteristic x-ray lines of the atoms present in the sample. By measuring the number of x-rays in the characteristic peaks of different elements, the composition of the sample can be determined. PIXE is capable of measuring concentrations to levels of about 1 ppm and can do so simultaneously for many elements in the same sample [1]. Therefore, being able to collect, analyze and compare spectra is a core part of the PIXE procedure. BYU has employed this technique to measure trace element concentrations in lichens, air particulates, mummy hair, and soils.

XRF

X-ray fluorescence or XRF spectroscopy shares many characteristics of PIXE, except that atoms are ionized by x-rays emitted by an x-ray tube, rather than by protons from the accelerator. Typically, the primary x-ray tube emits x-rays with a wide range of energies. These x-rays then hit a metal foil and the foil produces a secondary beam consisting mainly of characteristic x-rays from the foil. This secondary beam of x-rays then ionize atoms in a sample, which then emit characteristic x-rays of the sample that are collected in a solid state detector. At BYU, we use a Kevex Model 0700 XRF spectrometer. This spectrometer uses a lithium-drifted silicon [Si(Li)] detector, as Si(Li) detectors combine good energy resolution with high efficiency in the x-ray region [1]. XRF spectroscopy at BYU is frequently used for the qualitative analysis of a wide variety of samples. We have used XRF spectroscopy for preliminary analysis and not publication-quality studies.

Iron-55 (Fe-55) decays by electron capture only, making it a good sample for XRF spectroscopy. An electron is captured by the iron and turns a proton into a neutron, thereby turning Fe-55 into manganese-55 (Mn-55). Once the Fe-55 has decayed, we have a Mn-55 nucleus with an inner shell vacancy that gives off a Mn x-ray when the vacancy is filled. Therefore, by using an Fe-55 source, we can create a Mn-55 spectrum.

Gamma-Ray Spectroscopy

Gamma-ray spectra are also taken with solid state detectors for a variety of samples. At BYU, gamma rays are used to calibrate the energy of the van de Graaff accelerator, to determine the composition of gamma-emitting samples, and to detect gamma rays emitted by samples for particle-induced gamma-ray emission (PIGE) spectroscopy.

Solid State Detectors

A very important aspect of each of these applications is the detector. Solid state detectors work by producing large numbers of electron-hole pairs as charged particles pass through them. The emitted photons interact with the detector crystals through a mix of Compton scattering, the photoelectric effect and pair production. Their energy is transferred to electrons that are elevated from the valence band to the conduction band thereby producing electron-hole pairs. Solid state detectors work very well because there is little variation in the number of pairs produced (due to the large number of pairs) and this leads to good energy resolution, better than other detector types [2]. Since the atoms in PIXE samples give off x-rays, x-ray detectors are needed to collect the spectrum data. However, when the x-ray detectors were tested, the data acquisition systems (DAQs) proved to be outdated and not functioning as they used to. Therefore, in order to be able to compare the old systems with the digitizer, the decision was made to use a gamma-ray detector. The gamma-ray detector used is a

high-purity germanium detector, which is able to come to room temperature between uses. To test this system we used Ra-226 sources since radium and its daughters produce a large number of gamma rays with energies ranging up to 2.5 MeV.

Previous Methods

The process of creating spectra before waveform digitizers was a bit complicated. After being detected the signals from the solid state crystal would travel through a preamplifier, then into an amplifier before being routed through an analog to digital converter (ADC). After the ADC, the signal is read by a computer enabled with multi-channel analyzer (MCA) software that channels the data into the spectra. Before digitizers, spectra at BYU were created using a Genie DAQ system. The system worked quite well, giving about 3 percent energy resolution in the Mn K-alpha x-ray peak. This and similar systems do very well when new, but the technology has become outdated and is difficult to repair or update. For this reason waveform digitizers (usually just called digitizers) may be less expensive and easier to use; however, whether or not they are compatible with solid state photon detectors needs to be addressed.

1.3 Purpose

The purpose of my thesis is to evaluate the use of digitizers with solid state detectors. Digitizers simplify the process by allowing signals to be routed directly to the computer, rather than having to go through an analog port before being digitized. Also, digitizers work in a very different way than traditional spectrum analysis. Traditionally, the preamplifier and amplifier conditioned the pulses from the detector; then the peak height or area of the pulse was converted to a digital representation so that it could be stored in a spectrum. On the other hand, a waveform digitizer samples a

peak at short intervals (in our case, 4 ns) and converts each sample into an array of numbers. We can analyze the data digitally to obtain information about the pulse such as peak height, area, and pulse shape. Digitizers have been primarily used where pulse shape discrimination is important to distinguish between pulses produced by different samples, such as neutrons and gamma rays. Since digitizers convert every pulse into a string of numbers, they have not been able to handle high count rates and computers have not been able to store spectra with large numbers of counts, but in the latest generation of digitizers and computers, many of these difficulties are being solved. Digitizers can still be useful where the shape of the pulse is not important because the pulses can be processed in software without the limitations imposed by hardware processing.

Since digitizers are a relatively new technology (much younger than PIXE itself), their performance needs to be compared to the previous process of collecting and compiling spectra. To evaluate the suitability of digitizers in these applications, we wished to measure the energy resolution and maximum count rate obtainable by the digitizer. For a waveform digitizer to be suitable for data acquisition, we would require its performance in each of these areas to be as good as previous systems.

Since the end goal is PIXE analysis, an x-ray detector was the ideal detector for evaluating the digitizer. However, out of the x-ray detectors available, none of them provided adequate signals. The pulses from the x-ray detectors were too long and wide for the digitizer to handle. When we were testing the XRF, the pulses from the preamplifier needed to be processed before they could be put into the digitizer. The pulses exhibited a sawtooth pattern [see Fig. 1.1(a)] where the periodic drop was much larger than the pulses themselves. The sawtooth pattern was eliminated by using a timing filter amplifier (TFA), which differentiates the pulse. However, the sawtooth pattern was traded for a spike where the system resets and even more

processing needed to be done before it could be digitized [see Fig. 1.1(b)]. Also, due to the fact that taking the preamplifier signal through an amplifier creates too broad of a peak when using the XRF, my focus was shifted to a gamma-ray detector. This detector produced good signals that could be easily digitized.

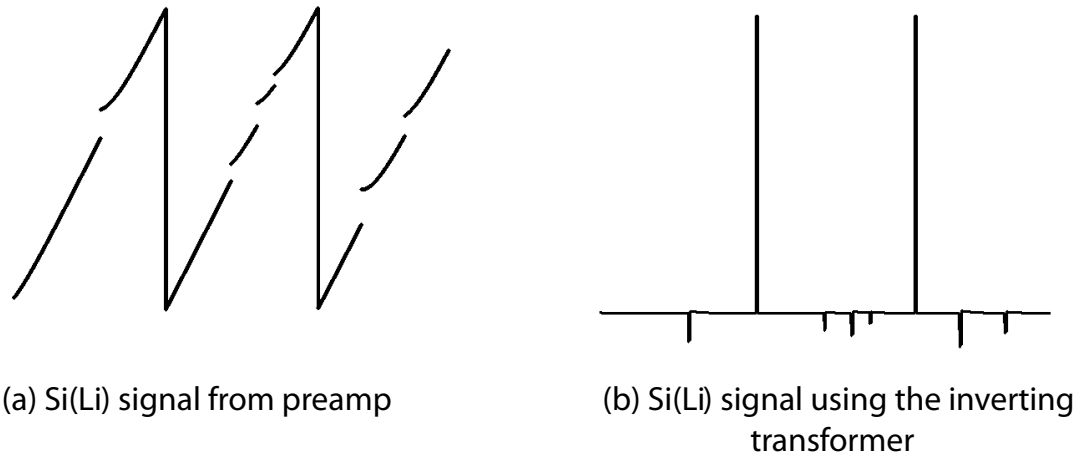

Figure 1.1 Signals from the Si(Li) Detector.

Chapter 2

Methods

2.1 Setup

In the evaluation of the digitizer, I performed tests to determine if the digitizer's count rates and energy resolution are comparable to the known methods. The gamma detector I used was a hyperpure germanium (HPGe) detector. The detector operation requires it to be cooled to liquid nitrogen temperatures and to be provided with a +4500 V bias. A preamplifier power supply is also required for the built-in preamplifier. When used with the digitizer, the signal from the preamplifier was passed through a feedthrough inverting transformer that differentiates the signal so that the pulses separate and become short enough for the digitizer to process. Without the inverting amplifier the pulses from the preamp have a quick rise but a long decay several microseconds long [see Fig. 2.1(a,b)]. The digitizer I used requires the input pulses to be 1 V or less, thus I did a preliminary check of the pulse before putting the output into digitizer. Our pulses had a maximum of about 0.2 V [see Fig. 2.1(c)]. We used radium-226 buttons as the gamma-ray source because the data is easily compared to published radium spectra.

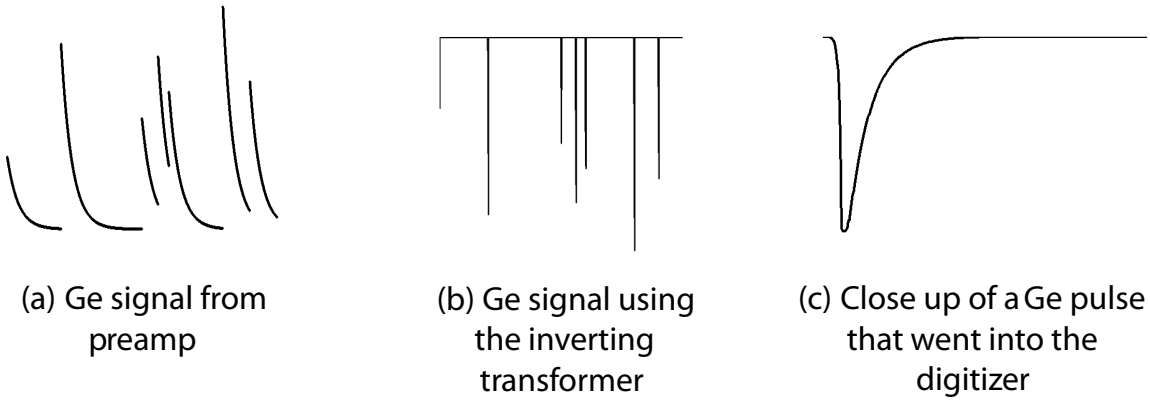

Figure 2.1 Signals from the Ge Detector.

2.2 Determining Energy Resolution

I performed initial tests to verify that the spectra produced by the digitizer were what we expected. I placed a radium source approximately 20 cm away from the end of the detector and collected a spectrum. I collected data for as long as was necessary to allow the peaks to become well defined. I then compared this spectrum to published radium spectra and confirmed that the spectra looked as they should. From the spectra collected, I was also able to determine the energy resolution.

2.3 Determining Maximum Count Rate

To determine the maximum count rate the digitizer could handle, I employed two procedures. For the first method, I placed the radium source at certain distances from the front of the detector, took a spectrum, then moved the source to a different distance from the detector and repeated the process. I checked to see if the count rate dropped with solid angle as expected. The second method I used required two radium sources. I took data from each source separately and then from both sources

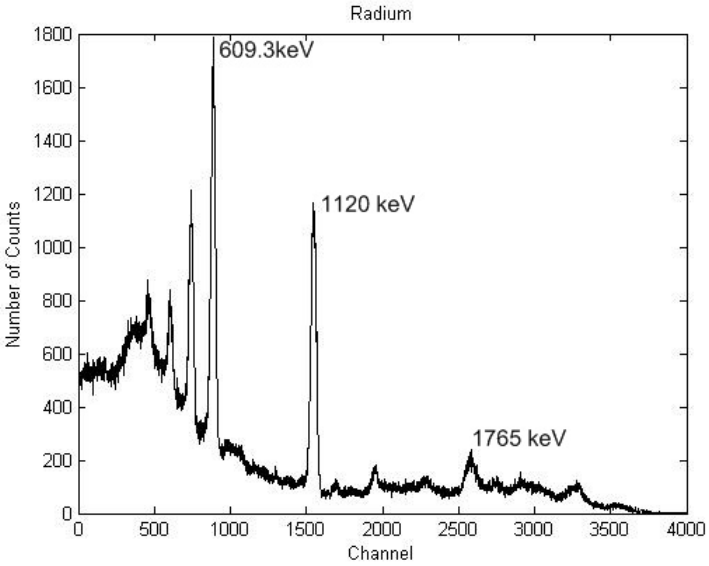

Figure 2.2 Radium Spectrum.

together to see if the combined count rate was the sum of the individual count rates. Using these two methods, I hoped to determine the maximum number of counts the digitizer will handle.

Method A

For the first method, the source placement ranged from approximately 5 to 30 cm from the detector and I moved the source a few centimeters after each spectrum was collected. The decay process that produces gamma radiation is one that happens randomly and therefore we wanted each spectrum to have roughly the same amount of uncertainty. If we collected data for a short amount of time we would get varying results due to statistical variation. The uncertainty in the number of counts in a peak is given by Poisson statistics and is approximately the square root of the number of counts in the peak. I aimed for an uncertainty of 1 percent, meaning that if 10,000 counts were taken, then the uncertainty would be $100/10,000 = 0.01$. I then plotted the total number of counts per second times distance squared versus the distance

($cps * R^2 = \frac{counts}{seconds} * distance^2$) and we seek a relatively linear relationship, with a drop or rise in the count rate very close to the detector.

Method B

For the second method, I placed source A in front of the detector and took a spectrum; I then replaced source A by source B. I moved Source A far away and gathered a spectrum of source B for the amount of time necessary to ensure the same amount of uncertainty. I brought Source A back and took a spectrum of both sources together, again obtaining the same uncertainty. Both the distance and time of each run were recorded. I placed the sources at varying distances following the same pattern as with the first method. The total number of counts per second was determined for each spectrum. I added the total number of counts per second together for sources A and B at each distance and subtracted that sum from the total number of counts per second for the spectrum of both sources together ($Difference = cps(AandB) - (cps(A) + cps(B))$. We expected the difference to be zero far from the detector until we reached the distance where the digitizer has met its maximum count rate.

There was greater variation from point to point than expected with these data, so we refined the method and took the data again. On the second round, I placed source A on the left half of the area in front of the detector, and source B on the right half. This ensured that when the counts were added together for both the A and B spectra, the placement did not have anything to do with the varying counts. Also, each spectrum I collected at a specific distance was taken for a specific time to hopefully make the calculations easier.

Chapter 3

Results

3.1 Energy Resolution

The first aspect we wanted to measure was the energy resolution of the gamma-ray detector. Energy resolution from gamma-ray detection is determined by the full-width at half-maximum (FWHM) of the peaks and is usually expressed as a percentage. The FWHM (measured in energy) is divided by the energy of the peak and then multiplied by 100. The energy resolution for the 690 keV peak in the radium spectrum ranged from about 2 to 3 percent. Ideally, we want the energy resolution to be about 1 percent, but since we did not do anything to optimize the resolution of the detector, a resolution of 2 to 3 percent suggests that the digitizer is performing as well as can be expected.

3.2 Maximum Count Rate

Count Rate with Method A

The next thing we wished to determine was whether or not the digitizer could

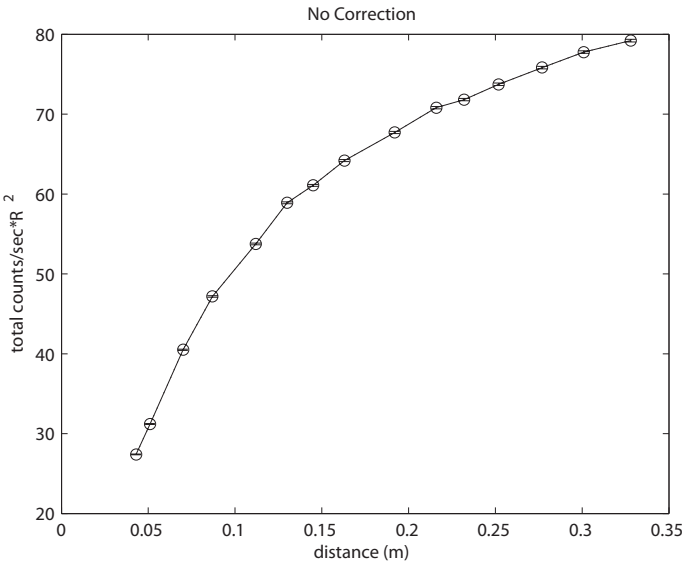

Figure 3.1 No correction for the distance was made for this graph.

handle high count rates. The first method we employed was to place the radium sources at variable distances from the detector, as described in Chapter 2. If we ignore second-order effects (such as multiple scattering and the active volume of the detector varying with source distance) the number of gamma rays reaching the detector should be inversely proportional to the square of the distance from the source to the detector. We were interested in total count rates, and therefore, we needed to sum all the counts in the gamma-ray spectrum. The actual count rate is slightly higher than this because higher energy gamma rays were not recorded in the spectrum. Also, since we collected data for longer periods of time when the source was more distant from the detector, we needed to make a correction for background gamma events. We accounted for the background gamma events by taking data with no source present and subtracting out the measured background scaled to the actual collection time for each run. One thing we did not know, however, was the distance from the window of the detector to the

germanium crystal. Initially we ignored this distance and used the distance from the window to the source in our calculations. Fig. 3.1 shows the count rate multiplied by this distance squared as a function of distance. If only solid angle effects are important, this value should be a constant until the observed count rate starts falling when the source gets close to the detector. However, it is easily seen that no part of the graph is flat, implying either that the efficiency of the system highly depends on count rate or that we have failed to take other effects into account. Typically,

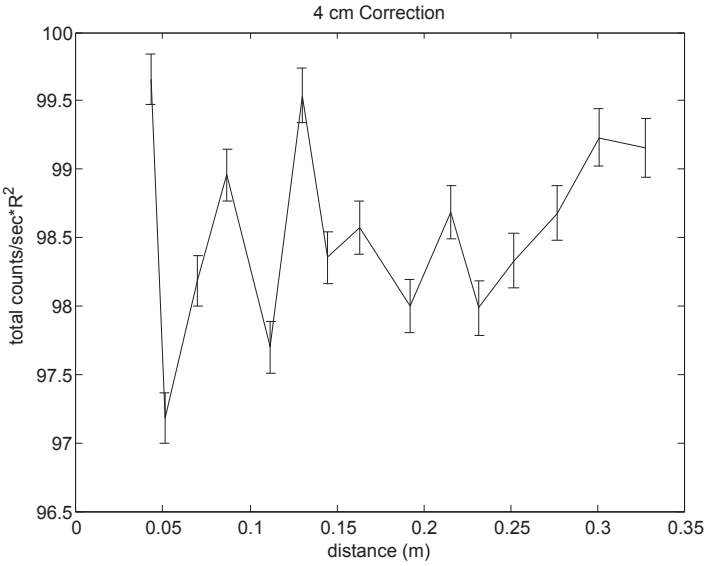

Figure 3.2 Same graph as above except with a 4 cm correction.

there is about 4-5 mm between the window and the crystal and in an attempt to account for this, I added an arbitrary amount to the distance from the window to the source until the graph showed a constant where the count rates are low (at farther distances). This analysis suggests that the crystal lies about 4 cm inside the window (see Fig. 3.2). However, this is roughly 3.5 cm farther than the typical value. The huge difference led us to believe that the correction is more than geometrical and that the maximum count rate cannot be determined this way and that Method B would

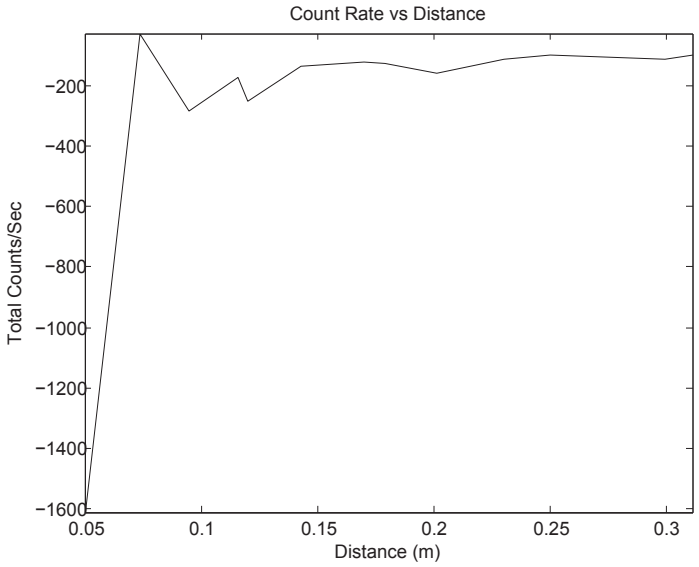

Figure 3.3 The negative data shows that we lost counts when both sources were present.

be better.

Count Rate with Method B

Similar to Method A, the spectra were summed to find the total number of counts. In these runs data were taken for the same amount of time with source A, source B, and both sources together, making background subtraction unnecessary. (The background is just part of the total count rate.) Ideally the number of counts with both sources would be the same as the sum of the counts from each source individually. This would mean that the system had not yet reached its maximum count rate. We consistently got a negative difference, meaning that we were consistently losing counts when both sources were present. This effect, however, is quite small and is not consistent with the digitizer reaching its rate limit at low count rates. (See Fig. 3.3) We calculated the percent difference and graphed it verses the sum of the count rates of both sources (See Fig. 3.4). An explanation of the error bars is included in Appendix A.). Again, the percent difference is negative throughout and we can see

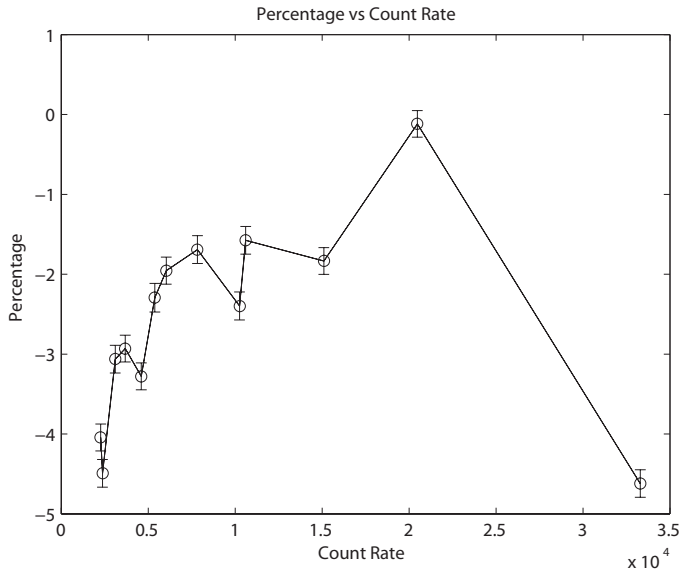

Figure 3.4 The negative percent data shows that we lost counts when both sources were present.

that the difference stayed within about 5 percent, therefore not many points were lost. We would expect the percent difference to be greater for larger count rates, but the data seems to show the opposite. The last data point in Fig. 3.4 does show a more significant loss of counts than the other points. It is possible that the digitizer is not able to handle a count rate of 30,000 counts per second. Taking all this into account, we can conclude that the waveform digitizer system can handle count rates of at least 20,000 counts/sec before we start losing counts.

3.3 XRF

We tested the XRF spectrometer with an iron-55 source that produces characteristic manganese x-rays. Mn K-alpha x-rays have an energy of 5.90 keV. The preamplifier in this system produces a sawtooth waveform with individual pulses superimposed on it (Fig. 1.1). This results from the charge on the detector collecting for a period

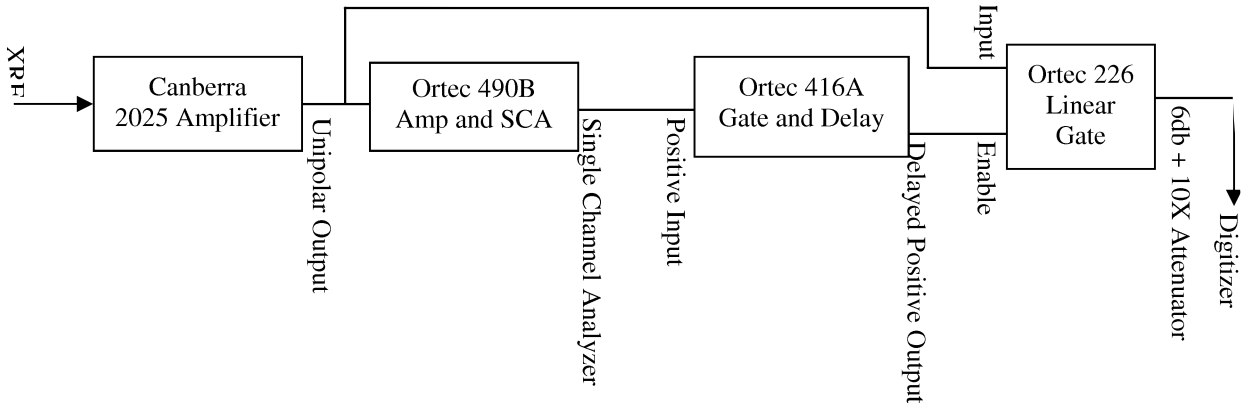

Figure 3.5 Block Diagram.

of time until it is reset by the electronics. Using the same inverting transformer that we used for the gamma-ray detector, the resets produced sharp spikes that had too large a voltage for the waveform digitizer. And attenuating the signal left the x-ray pulses too small to be useful. Close to the publication date of this thesis, a process of obtaining pulses short enough to be digitized has been discovered. A block diagram of the setup is shown in Fig. 3.5. The Canberra 2025 amplifier has a reset switch (the AFT) that when set to "Reset Preamp" eliminates the sawtooth pattern. After coming out of the amplifier the pulse is about 20 micro seconds wide, too wide for the digitizer to handle. The Ortec 490B Single Channel Analyzer checks for pulses between two voltages (an upper bound and a lower bound) and gives out digital pulses if they lie within that range. The Ortec 416A Gate and Delay Generator then uses the pulse as a gate pulse (making it more square). With a wider gate, more pulses can be allowed through the system. The Delay Generator puts a delay in the digital signal so that both the analog and digital signals arrive at the Linear Gate at the same time. Digital signals are generated more quickly than analog signals, so the

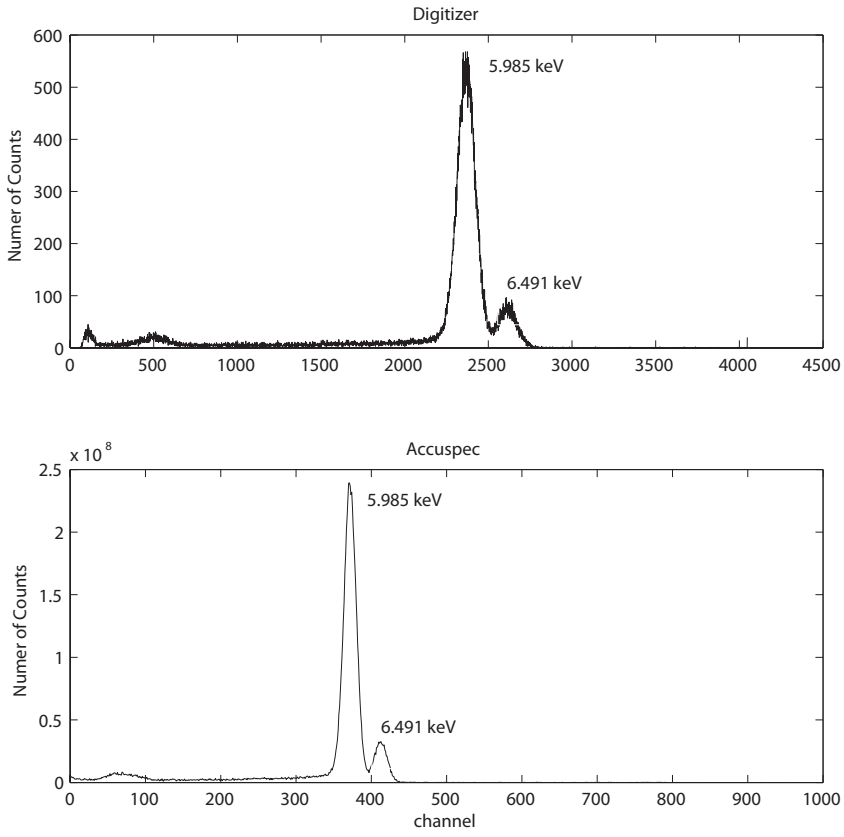

Figure 3.6 Graph comparing Accuspec with the Digitizer.

delay is required to get signals out of the Linear Gate. The Ortec 426 Linear Gate amplifies and narrows the pulse before putting the pulse into the digitizer, the signal is attenuated by a 20-times attenuator that lowers the maximum voltage from about 8 V to about 0.4 V. From this we were able to get an Mn-55 spectrum and compare the results of the digitizer with a Canberra Accuspec MCA.

Results and Data

With the Accuspec system, the resolution was found to be about 5.256 percent and with the digitizer, we got an energy resolution of 5.139 percent. The two results are very close, but the Accuspec spectrum is visually superior. (see Fig. 3.6).

3.4 Conclusion

Waveform digitizers work in the sense that they correctly compile and create spectra. A count rate of 20,000 counts per second is perfectly adequate and suitable for most applications, making count rate not an issue for the performance of the digitizer. The resolution of the gamma-ray peaks is most likely limited by the detector rather than the digitizer and can be improved by working with the detector. The poor resolution of the x-ray peaks is most likely due to the complex processing of the signal, leading us to believe the digitizer is still capable of producing good energy resolution with better signals. The challenge resides in the fact that signals from the preamplifiers need to be processed before entering the digitizer. For the gamma-ray detector, the solution was as simple as using an inverting transformer to differentiate the system and make the pulses short enough for the digitizer to handle. In the case of the x-ray detector, however, the trouble with the preamplifier is much more challenging. These preliminary results are encouraging, but in order to make waveform digitizers useful for spectroscopic applications, work needs to be done to optimize and simplify the processing of the signals from the preamplifier.

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Appendix A

Error Bar Calculation

An algorithm for determining the error bars in Fig 3.4 is described below. We first find the percent error of the counts per second for the difference between both sources together and when sources A and B are summed. Let A be the count rate of source A, B be the count rate of source B, and Both be the count rate of both sources together. So the percent error is given by

$$P = \frac{Both - A - B}{A + B} * 100$$

. We then take the derivative of the percent error with respect to A, B, and Both.

$$DpA = \frac{\partial P}{\partial A} = \frac{Both}{(A+B)^2}(-100)$$

$$DpB = \frac{\partial P}{\partial B} = \frac{Both}{(A+B)^2}(-100)$$

$$DpBoth = \frac{\partial P}{\partial Both} = \frac{100}{A+B}$$

Once the derivatives are found, the length of the error bars is given by:

$$\Delta P = \sqrt{(DpA\sqrt{(A)})^2 + (DpB\sqrt{(B)})^2 + (DpBoth\sqrt{(Both)})^2}$$

where it simplifies to

$$\Delta P = \sqrt{\frac{Both(A + B + Both)}{(A+B)^3}} * 100$$

.