

*Comparisons of the
Portable Digital Spectrometer Systems*

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by

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Abstract

Previous experimental evaluations [1,2] of ten commercial gamma-ray spectroscopy systems demonstrated significant benefits of digital signal processing for improvements in the performance of high-resolution gamma-ray spectroscopy systems. Spectacular improvements in the energy resolution and throughput of germanium detectors were demonstrated for the DSPEC, DSPEC Plus, and 2060DSP. Recently, two new portable DSP spectrometer systems were developed. Results of the performance of these two systems are presented and compared to those of the DSPEC Plus and the analog NIM systems.

I. Introduction

Traditional gamma-ray spectroscopy uses an analog amplifier to process the pulses from the preamplifier in order to remove noise, reject pile-up signals, and shape the signals into some desirable forms before sending them to the analog-to-digital converter (ADC) to be digitized. Unlike the case in analog spectroscopy, digital signal processing (DSP) systems directly digitize the pulses from the preamplifier and then filter and optimize the digitized signals using digital processing algorithms. In 1996, EG&G Ortec (now Perkin-Elmer) introduced a Digital Gamma-Ray Spectrometer (DSPEC) that uses digital technology to analyze the preamplifiers' pulses from all types of germanium, silicon, and NaI detectors. Shortly afterward, Canberra Industries also released its version of the DSP system, the model 2060 Digital Signal Processor and the model 9660 ICB Programmable Digital Signal Processor. The DSPEC is an AC-powered, stand-alone multichannel analyzer (MCA) and the 2060DSP and 9660DSP are standard nuclear instrumental methods (NIM) modules, which must include other NIM modules to form complete MCA systems. Subsequent to their initial offering, these DSP systems were upgraded, repackaged, and released as the DSPEC Plus (Ortec), DSA1000 and DSA2000 (Canberra). These DSP systems perform much better than any analog system when used with a germanium detector. Spectacular improvements in the energy resolution and throughput of the germanium detectors were demonstrated in references 1 and 2.

All the above systems are full-size, AC-powered MCAs or parts of full-size MCAs. Recently, Canberra Industries and Perkin-Elmer Ortec have introduced two portable, standalone digital MCAs, the Inspector 2000 from Canberra and the DigiDART from Ortec. In this report, we present results of testing the systems with a coaxial and a planar germanium detector. We have also compared their performance against an analog NIM and a DSPEC Plus, acting as reference systems. Figure 1 shows three DSP systems used in this evaluation.



Figure 1: The three DSP systems used in the evaluation. From left to right are the DSPEC Plus, DigiDART, and Inspector 2000. An IBM notebook computer is located on top of the DSPEC Plus.

II. Spectroscopy Systems

A. Multichannel analyzer (MCA) descriptions

1. NIM

The NIM system was a standard system which consisted of an Ortec 4002D NIM bin power supply, Canberra 3106D HV power supply, Ortec 672 Spectroscopy Amplifier, Canberra 8706 ADC, Canberra 8233 Digital Stabilizer, Ortec 996 Counter Timer, and Ortec Ethernim MatchMaker. The triangular shaping of the amplifier was used for all the data collection. The BLR was set to “auto.” The maximum memory size for this system is 16K channels.

This NIM system, with the MatchMaker, can be connected to the computer by means of an Ethernet BNC connector, DPM 37-pin D-type connector, or low-speed serial link.

2. DSPEC Plus

DSPEC Plus is an AC-powered, stand-alone unit. Unlike in traditional signal processing where the pulses from the preamplifier are processed by the analog amplifier and then digitized by the ADC, DSPEC Plus digitally processes the pulses directly from the preamplifier using a quasi-trapezoidal pulse shape. The four parameters controlling the pulse shape are rise time, cusp, flattop, and tilt. There are 115 rise and fall times ranging from 0.2 to 23.0 μs in 0.2- μs steps, 21 flattop times ranging from 0.3 to 2.4 μs in 0.1- μs steps, and 7 cusp values ranging from 0.4 to 1 in 0.1 steps. All these values are computer selectable. The rise time of the DSPEC Plus is roughly equivalent to twice the integration time set on a conventional analog spectroscopy amplifier. The cusp controls the curvature of the sides of the quasi trapezoid, and the flattop adjusts the width of the top of the quasi trapezoid. The cusp and flattop values can be adjusted to obtain the best results for different detectors, radiation sources, or count rates. The tilt controls the flattop slope, and the DSPEC Plus optimizer automatically sets its value. The Baseline Restorer (BLR) of the DSPEC Plus can be set to auto, fast, slow, or manual. It was set to auto for this evaluation. The DSPEC Plus also has a built-in “Virtual Oscilloscope” (viewed with the Maestro software from Ortec) that would eliminate the need for an external oscilloscope. The maximum memory size is 16K channels.

Each DSPEC Plus processes the output of a single detector. DSPEC Plus can be connected to the computer by means of an ethernet BNC connector, Dual-Port Memory (DPM) 37-pin D-type connector, or low-speed serial link. If there is more than one DSPEC Plus-controlled detector, multiple systems can be set up under the control of one computer, by chaining all the detectors into a single local area network (LAN) using the Ethernet data link connection method. Likewise, using a LAN, multiple computers can be set up to receive data from and control single or multiple DSPEC Pluses. The DSPEC Plus can also communicate with the computer using the DPM data link. It requires a DPM interface card such as the Advanced Data Collection and Management (ADCAM) card from Ortec, which plugs into the host computer. If the DPM data link is used, it is still easy to connect up to eight DSPEC-Plus-controlled detectors or many other combinations of Ortec multichannel buffers (MCB) to one computer. A dual-port fan-out module is needed to adapt the single connector on the interface card into enough connectors for the multiple systems. The serial link of the DSPEC Plus is provided for convenience and debugging and is normally not used because of the low data-transfer speed.

The DSPEC Plus also features the zero dead-time (ZDT) mode of operation. When DSPEC Plus operates in the ZDT mode, it makes up for the live-time losses by taking very short acquisitions and applying a correction in real time to the number of counts in the spectrum. When operating in ZDT mode, the system stores both the corrected and uncorrected spectra. However, in ZDT mode, the throughput of the system is reduced somewhat as extra processing must be done on the spectrum.

3. DigiDART

DigiDART is a portable DSP system. The operating time on one battery is 9 h. DigiDART processes the pulses using a trapezoidal pulse shape. The three parameters controlling the pulse shape are rise time, flattop, and tilt. These are the same control parameters as found in the DSPEC Plus with the cusp value set to 1.0 (the side of the quasi trapezoid is a straight line with zero curvature). There are 97 rise and fall times ranging from 0.8 to 20.0 μs in

0.2- μ s steps, and 16 flattop times ranging from 0.5 to 2.0 μ s in 0.1- μ s steps. All these values are computer selectable. Note that the DigiDART does not employ the cusp parameter to control the curvature of the side of the trapezoid like the DSPEC Plus. One less parameter simplifies the operation somewhat but it may also affect the performance of the system.

DigiDART connects to the detector through the Detector Interface Module (DIM). The DIM includes the preamplifier and the high-voltage (HV) power supplies. The HV of the DIM is controlled from the DigiDART. Different DIMs that provide different HV bias ranges and polarities—designed for specific detector types—are available from the manufacturer.

DigiDART connects to the computer through the Universal Serial Bus (USB). Windows NT does not support USB, and the USB controllers of Windows 95 are so primitive that it does not recognize the DigiDART USB connection. Windows 98 and later Windows operating systems are required to run DigiDART. Similar to DSPEC Plus, DigiDART also features the ZDT mode of operation.

One additional feature that makes the DigiDART unique is that it has the built-in 240 \times 160-pixel LCD display and numeric keypad. In its internal memory it can also hold 23 16K spectra or 614 spectra at 512-channel resolution. This feature, coupled with long battery life, allows it to perform a variety of in-field measurements without a computer attached.

4. Inspector 2000

Inspector 2000 is a portable DSP system. The operating time on one battery is 10 h. Like the DigiDART, the Inspector 2000 processes the pulses using a trapezoidal pulse shape with two parameters: rise time and flattop. In a sense, it is similar to the DigiDART with the tilt value of zero (the flattop's slope is zero). There are 40 rise and fall times ranging from 0.4 to 38.0 μ s with the step size dependent on rise time range—small step size for small rise time and large step size for large rise time. There are 21 flattop time selections ranging from 0 to 3.0 μ s in variable steps. All these values are computer selectable.

Inspector 2000 connects to the computer through the USB or serial port. Like the DigiDART, if the USB connection is used, then Windows 98 or later is needed. If the serial link is used, then Windows 95 and NT can also run the system.

One useful feature is that the Inspector 2000 also employs a Pileup Rejector (PUR) Guard function, which proved to be effective in optimizing the system. The PUR interval is defined as $[X \times (\text{rise time}) + (\text{flattop})]$ where X is the PUR Guard time selection. There are eight PUR Guard time selections ranging from 1.1 to 2.5. Increasing the PUR Guard time extends the PUR interval to protect subsequent events from being corrupted by anomalies associated with the tail of the previous event. The throughput is also reduced as the PUR Guard time is increased. The user therefore should take into account the tradeoff between the resolution and throughput when setting the PUR Guard.

Note that for these DSP systems, the cusp and tilt parameters affect the resolution of the systems but not the throughput. The flattop and rise time parameters do have effects on both the resolution and throughput. Therefore, proper parameters are important in optimizing a system for best performance. Depending on other parameters and the input count rate, changing one parameter may improve or degrade the resolution of a system. It is also possible for one parameter change to affect resolution differently at different energy ranges—improving (or

degrading) in one range, while degrading (or improving) at another. With respect to the throughput, the rule is that increasing the flattop or the rise time will decrease the throughput. The effect of the flattop on throughput is almost the same as the effect of the rise time on throughput. From our measurements, we determine that the flattop width's effect on throughput is about 95% that of the rise time. That is, a flattop change of 1 μ s would have the same effect on throughput as a change of 0.95 μ s of the rise time. In other words, the throughput is a function of (rise time + 0.95 \times flattop).

Table I shows a summary of the specifications of the four systems.

Table I. Specifications of the spectrometer systems.

	NIM	DSPEC Plus	DigiDART	Inspector 2000
Shaping/rise time (μ s)	0.5, 1, 2, 3, 6, 10	0.2–23.0, step 0.2	0.8–20.0, step 0.2	0.4–38.0, variable steps
Pile-up rejector	yes	yes	yes	yes
Baseline restorer	auto, PZ, high	auto, fast, slow, man	auto, fast, slow, man	auto, hard, med, soft
Pole zero	auto, manual	auto, manual	auto, manual	Semi-auto
Stabilizer	zero, gain	zero, gain	zero, gain	zero, gain
ADC gate	yes	yes	no	no
ADC	450-MHz Wilkinson	N/A	N/A	N/A
ADC channel (max)	16K	16K	16K (32K optional)	16K
High voltage	\pm 5kV Ge, \pm 2kV NaI	\pm 5kV Ge	\pm 5kV Ge, +1.3kV NaI	\pm 5kV Ge, \pm 1.3kV NaI
HV inhibit/ control by	Ortec, Canberra / Hardware	Ortec, Canberra / Software	Ortec, Canberra / Software	Canberra / Software
Amp. polarity switch	external	software	software	software
Power supply	AC	AC	9-h Lithium-ion	10-h Lithium-ion
Dimensions, include battery pack (cm)	48x54x22	32x36x14	15x10x6	18x22x4
Weight (kg)	23.2	7.7	1.1 include DIM	0.7
Computer interface	ethernet, 37-pin DPM	ethernet, 37-pin DPM	USB, optional RS-232	USB, RS-232
Computer operating software & system	Maestro with Windows 95 or later	Maestro with Windows 95 or later	Maestro with Windows 98 or later	Genie-2000 with Windows 95 or later
Manufacturer	Ortec and Canberra	Perkin-Elmer Ortec	Perkin-Elmer Ortec	Canberra Industries
Price (\$1000)	~ 15	13	10 + 1.5 for 3 DIMs	10

B. Detector descriptions

Table II. Specification of the detectors. The specified resolutions are the warranted values from the manufactures.

Germanium detector	Coaxial	Planar
Manufacture	Canberra	Ortec
Manufacture date	Nov 1989	Jun 1999
Diameter (mm)	60.0	25.4
Length (mm)	42.0	16.2
Relative efficiency (%)	25	N/A
FWHM @ 1.33 MeV, 6 μ s shape, 1 kHz	1.75 keV	N/A
FWHM @ 1.33 MeV, 2 μ s shape, 1 kHz	1.94 keV	N/A
FWHM @ 1.33 MeV, 2 μ s shape, 30 kHz	2.00 keV	N/A
FWHM @ 122 keV, 6 μ s shape, 1 kHz	750 eV	N/A
FWHM @ 122 keV, 3 μ s shape, 1 kHz	N/A	510 eV
FWHM @ 122 keV, 2 μ s shape, 1 kHz	850 eV	N/A
FWHM @ 122 keV, 2 μ s shape, 30 kHz	880 eV	N/A
FWHM @ 122keV, 1 μ s shape, 50 kHz	N/A	580 eV

Two detectors, one coaxial and one planar, were used for the evaluation. Table II lists the specifications of these detectors. The performance of the 25% coaxial detector is degraded at high energy, its values much worse than that listed in Table II.

C. Software description

The software used to acquire data with the NIM,

DSPEC Plus, and DigiDART was Maestro v5.3 from EG&G Ortec. The software for the Inspector 2000 was Genie-2000. The NIM and DSPEC Plus were connected to the computer through the Ethernet, the DigiDART through the USB port, and the Inspector 2000 through the serial RS-232 port in these experiments.

III. Testing the Systems

A. Resolution and throughput

1. Data acquisition

The planar and the 25% coaxial germanium detectors were used in the measurements (see Table II). Except for their front surfaces, the detectors were shielded with lead bricks and cadmium sheets to reduce the background gamma rays. Cobalt-57 (with energy peaks at 122 and 136 keV) and cobalt-60 (with energy peaks at 1173 and 1332 keV) were used. For these measurements, each source was measured separately. The sources were moved closer to or farther away from the detectors in order to achieve the desired count rates. When acquiring data with the ^{60}Co source, the conversion gain and range were set at 8K on all the systems; for the ^{57}Co source, the conversion gain and range were set at 4K on all systems. The amplifier gains were adjusted so that for the ^{57}Co data the 122-keV peak was at about channel 3200, and for the ^{60}Co source, the 1332-keV peak was at about channel 7800. The stabilizers were not used.

Shaping times of 1, 2, and 3 μs were used for the planar detector, and shaping times of 2, 3, and 6 μs were used for the coaxial detector. The input count rates were at 3, 10, 30, 60, and 100 kHz. Starting parameters for the decay time, flattop, tilt, and cusp were optimized for the range of shaping times and set at the start of each set of measurements. The pole-zero (PZ) and decay-time parameter were automatically adjusted for optimized performance for measurements at each of these shaping times. We also acquired data at higher input count rates, 100 and 150 kHz, using re-optimized starting parameters. The shaping times used at these high input rates were 0.5, 0.7, and 1.0 μs for the planar detector, and 0.5, 0.7, 1.0, and 1.4 μs for the coaxial detector. Because of the limited number of shaping time constants available with the NIM system, 0.5 and 1.0 μs were used for the NIM system at the high-count rates.

Note that the DSP systems (DSPEC Plus, DigiDART, and Inspector 2000) define rise times instead of the shaping times of the analog systems. The rise time of the DSP systems is roughly equivalent to twice the shaping time set on a conventional analog spectroscopy amplifier. Table III shows the equivalent shaping times and rise times for the four systems used in this evaluation. Some of the figures in this paper use the shaping time instead of rise time for the DSP systems. Table III converts these equivalent shaping times to the rise time for each of the DSP systems.

The reason for these equivalent shaping times and rise times is the following. The rise times of the DSPEC Plus and the DigiDART are chosen to be exactly twice the indicated shaping times except for the 0.5- μs shaping time. Because the electronics are somewhat different, the Inspector 2000 rise time is not quite equivalent to the same rise-time setting of the DSPEC Plus or the DigiDART. In general, for the same rise-time setup on both the Inspector 2000 and the DSPEC Plus (or the DigiDART), the Inspector 2000 would give somewhat better throughput. Therefore, to test equivalent systems, it is better to set the rise times on the systems such that the throughputs are about the same. Then the resolutions can be compared fairly.

Table III. Equivalent shaping and rise times (μs) of the systems.

Detector	Indicated shaping times	NIM shaping time	DSPEC+ rise time	Digi-DART rise time	I2K rise time
Planar	0.5	0.5	0.8	0.8	0.8
	0.7		1.4	1.4	1.2
	1.0	1.0	2.0	2.0	2.0
	2.0	2.0	4.0	4.0	3.6
	3.0	3.0	6.0	6.0	5.6
Coaxial	0.5	0.5	0.8	0.8	1.2
	0.7		1.4	1.4	2.0
	1.0	1.0	2.0	2.0	2.8
	1.4		2.8	2.8	4.0
	2.0	2.0	4.0	4.0	5.6
	3.0	3.0	6.0	6.0	8.4
	6.0	6.0	12.0	12.0	15.2

by the shapes of the pulses from the planar detector. Figure 2 shows the shaped signal obtained with the planar detector and a ^{57}Co source.

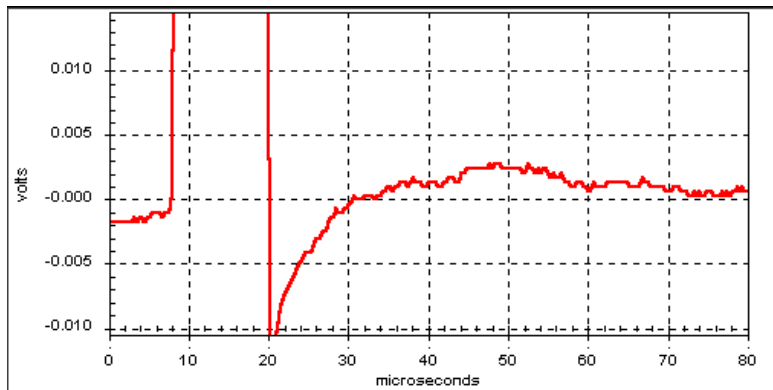


Figure 2: Output signal (volts vs. time) from the planar detector as displayed on the digital oscilloscope of the Inspector 2000.

As just mentioned, for the same rise-time setting, the Inspector 2000 would give better throughput. So for the same throughput (comparing with the DSPEC Plus), the rise time of the Inspector 2000 should be somewhat longer. This is apparent in the rise-time settings for the coaxial detector (see Table III). However, for the planar detector, the rise-time settings of the Inspector 2000 appear to be the same or even slightly smaller than those of the DSPEC Plus. This is caused

The undershoot on the trailing edge of the signal is large. An event that falls on the tail of another event will have a distorted pulse. If the PUR reject interval is small, that distorted signal will be recorded, with the result that the spectral peaks will have excessive low-side tailing, especially at high count rates. With the PUR Guard function in the Inspector 2000, the PUR Guard time can be increased to exclude events that arrive too

close to the tail of the previous pulse. This will reduce the spectral distortion, but the throughput will also be reduced.

We found for this planar detector that the PUR Guard time selection of 2.5 gives the best results, so we used it for all measurements with the planar detector. The rise times are also reduced to compensate for the reduced throughput. The coaxial detector does not exhibit this problem, so the PUR Guard time selection was kept at 1.1.

Triangular pulse shaping was selected for the NIM system on the Ortec 672 Spectroscopy Amplifier, and the Baseline Restorer (BLR) was set to “auto.”

There are many combinations of the rise, flattop and cusp parameters for the DSP systems. The optimal combination is different for each detector. Using the wrong values or combinations would lead to poor resolution and/or throughput. The user can either use the

suggested parameter combinations from the manufacturer or can determine the best parameters by experimenting with different settings. The shaping parameters were set as follows. The cusp was set at 0.6 for the DSPEC Plus. The flattop values were set at 0.8 μs and 1.0 μs for the planar and coaxial detector, respectively. These optimal values were determined previously for the DSPEC Plus operating with the germanium detectors [2]. A search for the optimal flattop setting at various rise times found 0.9 μs to be best for the DigiDART operating with either detector. A similar search done for the Inspector 2000 yielded the optimal flattop setting of 0.6 μs for the planar detector and 0.8 μs for the coaxial detector.

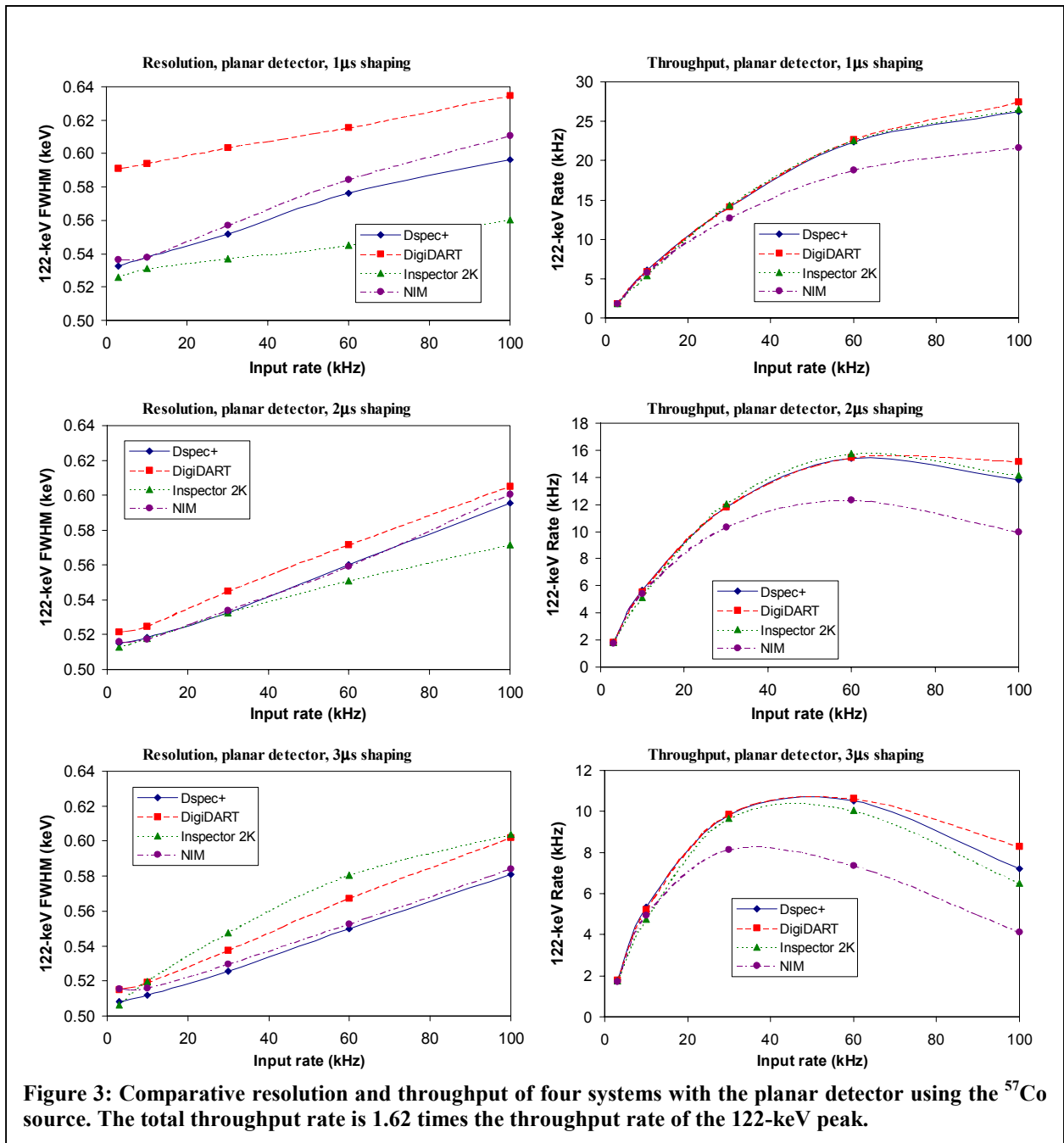
2. Analysis

The NIM, DSPEC Plus, and DigiDART systems run under Ortec's Maestro software and store the data in either the Ortec CHN or SPC formats. The Inspector 2000 uses the Genie-2000 software and stores the data in the Canberra CNF format. The Inspector 2000's files were converted to the Ortec CHN format and used with the analytical functions in Ortec Maestro software. The file format conversion allows the same analytical functions—from the identical software—to be applied to all data sets (so if there are any biases from the analysis algorithms, they should be the same for all the data sets). The energy calibrations were done using either the 122.06-keV and 136.47-keV peaks of ^{57}Co or the 1173.23-keV and 1332.49-keV peaks of ^{60}Co . The net counts in the 122-keV and 1332-keV peaks were used to calculate the throughput rate. Figures 3, 4, and 5 show the fitted resolution and throughput results of all three systems with both detectors. Analysis was done on the 122-keV peak of ^{57}Co and the 1332-keV peak of ^{60}Co for all spectra. The total throughput rates are 1.62, 1.72, and 14.0 times the throughput rates of the 122-keV peaks of planar and coaxial detector and 1332-keV peak of the coaxial detector, respectively.

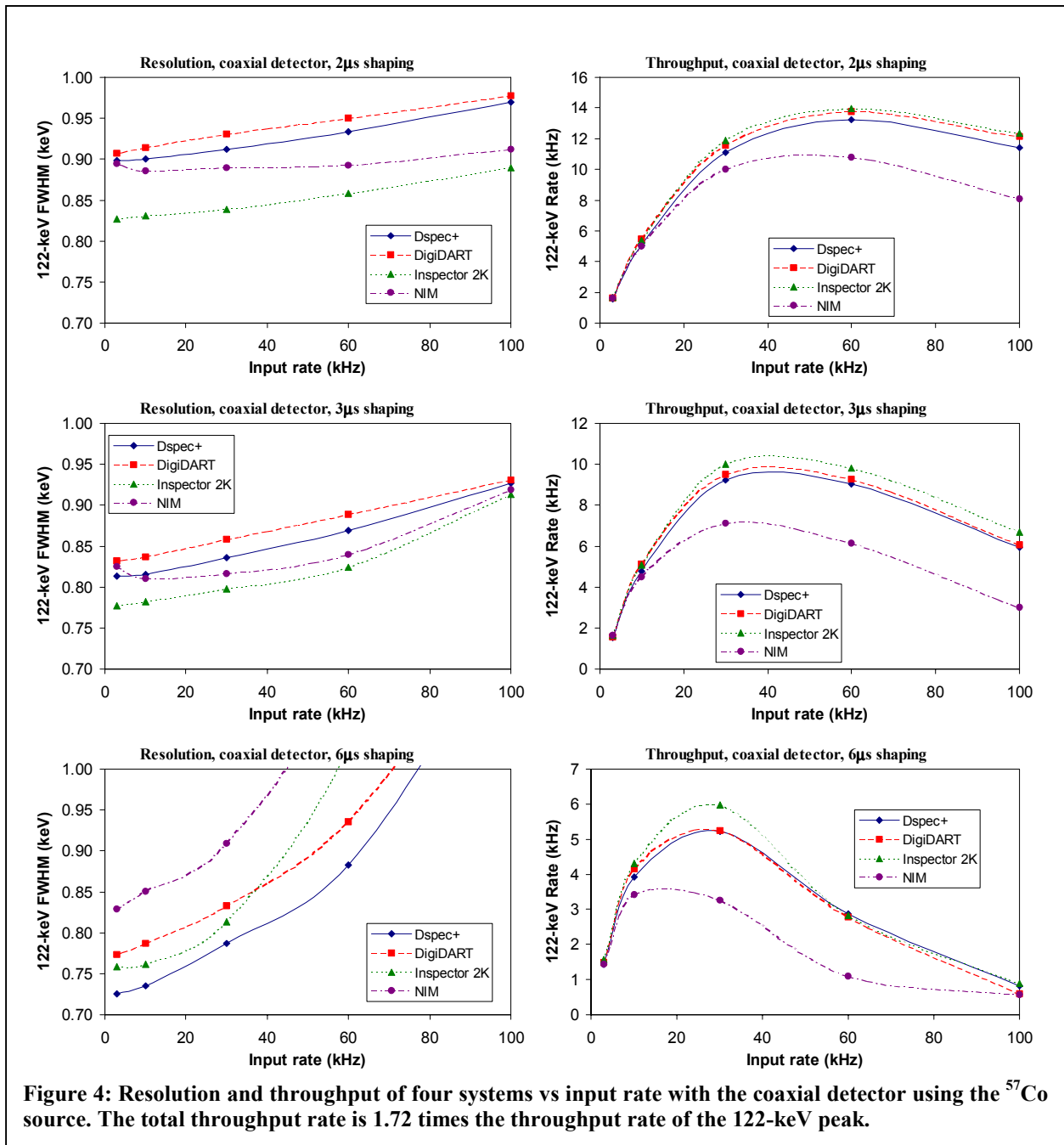
All three DSP systems have about the same throughput, which is much better than that of the NIM system at all input rates and shaping times. The reason the throughput is about the same for all the DSP systems is because they are all set up for similar throughput for easy comparison, as explained in section III.A.1.

We were told by the manufacturer that the DigiDART and DSPEC Plus have similar components and use the same technology, so the performance of both systems should be similar. The throughput rates with identical rise times are almost identical for the two systems. This confirms the claim.

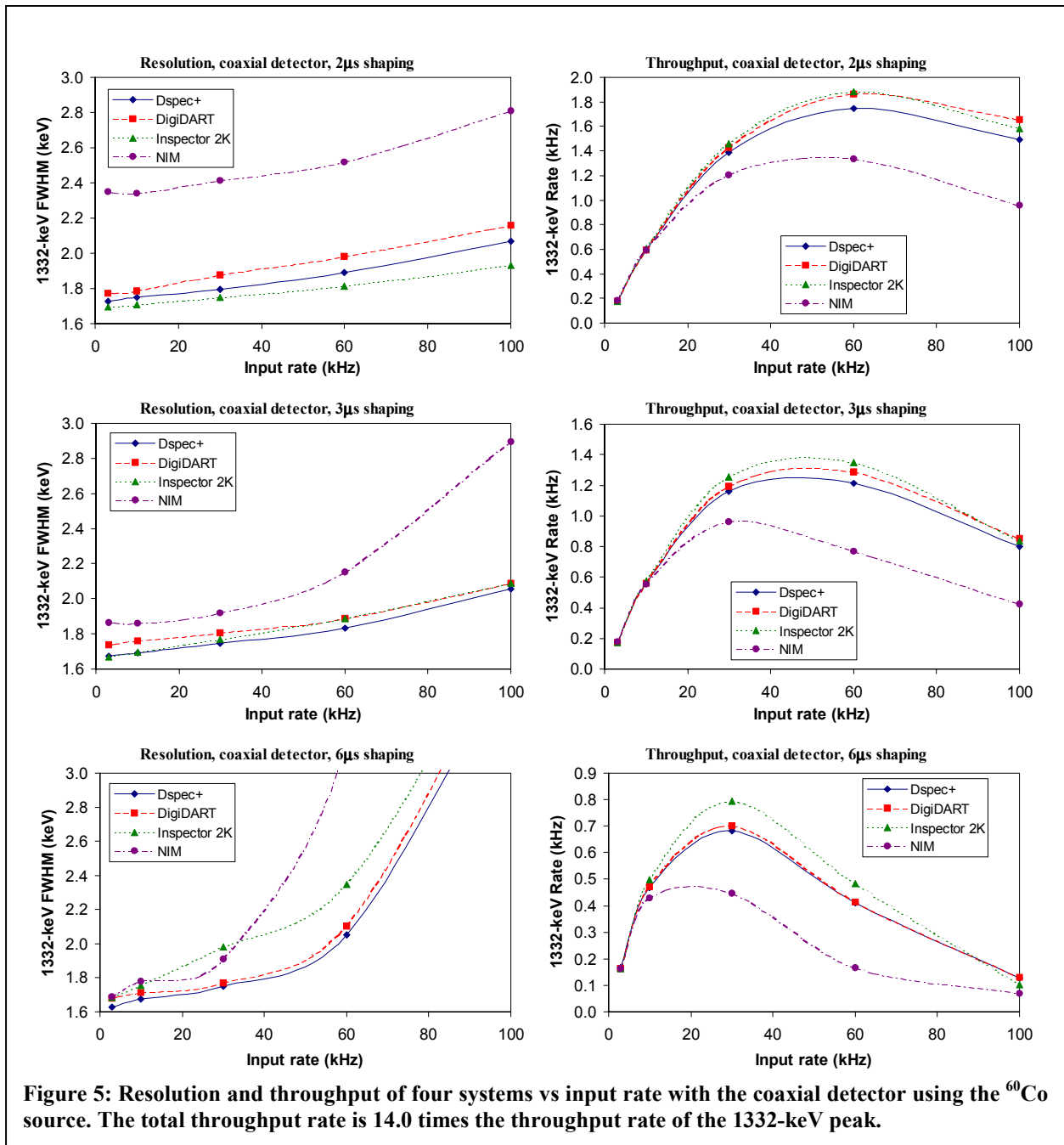
However, for the resolution comparison, the DigiDART appears to be slightly worse than the DSPEC Plus at all input rates and shaping times, except with the planar detector at 1 μs shaping time where it is almost 10% worse. Although these two systems use the same technology, it is not surprising that the DigiDART's resolution is somewhat worse than that of the DSPEC Plus. The DigiDART is about 10 times smaller and lighter than the DSPEC Plus. When the DSPEC Plus equivalent electronics are packed inside the small space of the DigiDART, the heat build-up and the effects of nearby components may degrade its resolution performance somewhat.



Upon close inspection, we see that for the planar detector at low energy (122 keV) and the coaxial detector at high energy (1332 keV), the DigiDART's resolution is somewhat worse than that of the DSPEC Plus at small shaping time. As the shaping time gets larger, the differences in resolution between the two systems become smaller. However, for the coaxial detector at low energy (122 keV), the behavior is opposite.



This probably means that the DigiDART is noisier than the DSPEC Plus when used with the coaxial detector. For a noisy system, when the shaping time is increased, the amount of electronic noise picked up and analyzed by the MCA also increases. Due to the larger noise to peak pulse for low peak energy, this noise interference affects the low-energy peak more than peaks with higher energy. At some point, the increase in noise with increased shaping time more than offsets the resolution improvement. Increasing the shaping time at this point degrades the resolution instead of improving it. This effect is more apparent with the NIM system, which will be described later. That noise interference effect probably explains the larger gap between the



DigiDART and the DSPEC Plus at large shaping time for the 122-keV peak obtained with the coaxial detector.

The resolution of the NIM system at low energy is comparable to that of the three DSP systems for both detectors. However, for high energy (1332 keV), its resolution is poor, especially with the small shaping time. This is caused by the large ballistic deficit effect of the coaxial detector. (Ballistic deficit occurs when the charge collection time of the detector exceeds the shaping time of the amplifier. This effect is greater with large detectors and high-energy gamma rays.) Increasing the shaping time reduces the ballistic deficit effect. However, even at

small shaping times, the energy resolution with the DSP systems is significantly better than that with the analog systems like the NIM. Improvements with the DSP systems derive in part from the equivalent of algorithmic extrapolations. This partly compensates for pulse rise times that exceed shaping times.

Figure 5 shows that for the coaxial detector at lower input rates up to 50 kHz, the shaping time of the NIM system needs to be at least 3 μ s for reasonable performance with high-energy sources. A shaping time of 3 μ s or less is required at higher input rates to achieve a reasonable throughput.

This NIM system also exhibits unusually large electronic noise effects with these two germanium detectors. Normally the long shaping time would give better resolution than the short shaping time at low count rates. However, the large shaping times are more susceptible to electronic noise effects. A system with large electronic noise effects may require a shorter shaping time for the best performance.

The results with the NIM system shown in Figures 3, 4, and 5 confirm this. The strongest evidence is in Figure 4 with the results at 122 keV for the coaxial detector. The resolution at 6- μ s shaping time is much worse than at 3- μ s shaping time, even at the lowest count rate.

A noisy system may also affect the performance in a different way. The NIM's results at 3- and 10-kHz input rates in Figures 3–5 are unusual. Except for the results with the coaxial detector at 6- μ s shaping time, the results show that the resolution measured at 3-kHz input rate is worse than that taken at 10 kHz. This indicates that the noise is independent of input rate, so that the noise-to-signal ratio at the low input rate would be greater than that at the higher input rate. This larger noise-to-signal ratio can offset the resolution advantage at low input rates.

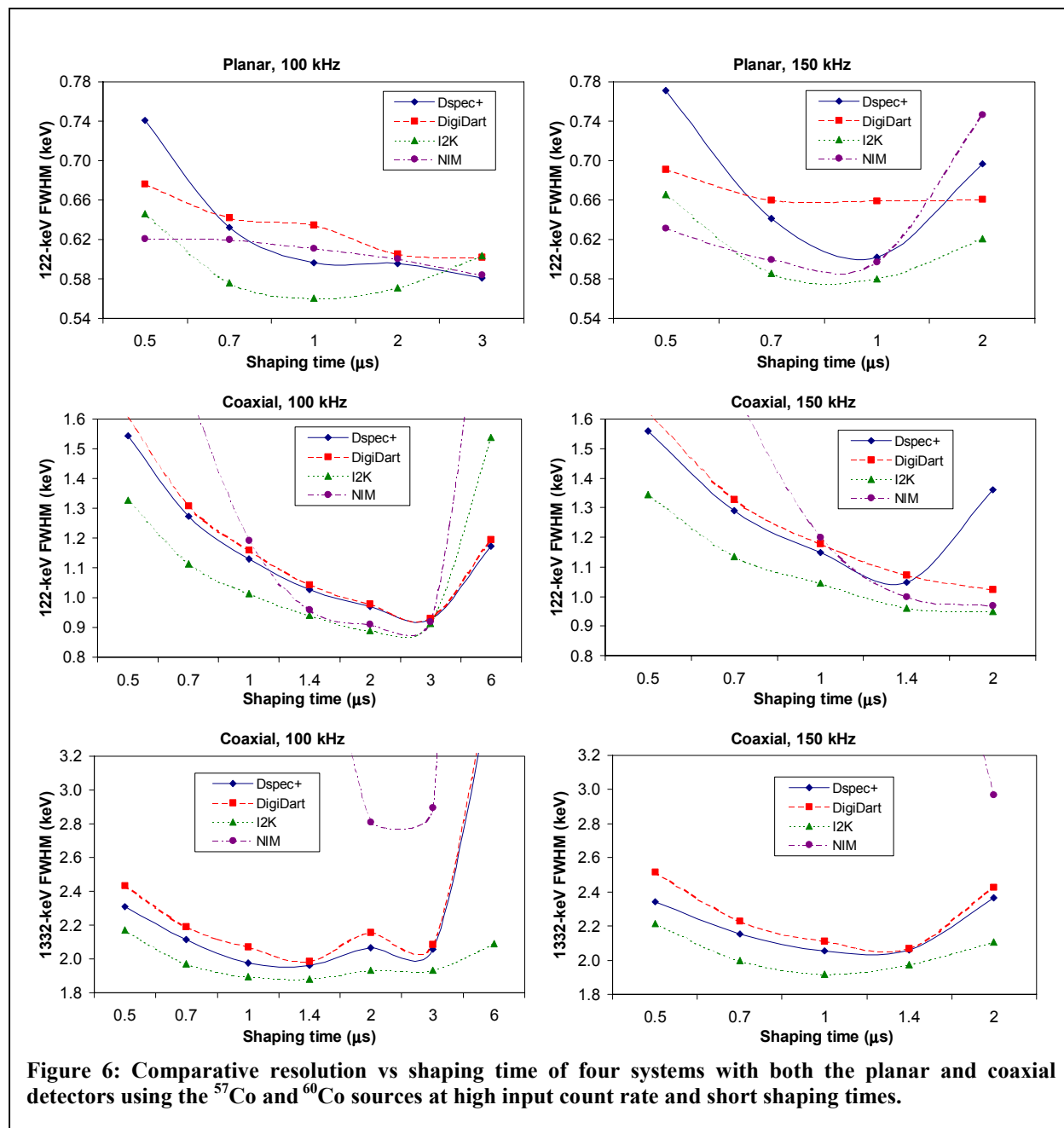
The Inspector 2000 seems to be slightly better than the DSPEC Plus at both low and high energy for both the planar and coaxial detectors when small shaping times are used. As the shaping time increases to larger values, the performance of the Inspector 2000 improves but at a lower rate than that of the DSPEC Plus or the DigiDART. At large shaping times, its resolution is worse than that of the DSPEC Plus and even the DigiDART.

This behavior may at first be attributed to the noise in the system. Upon closer examination, we see that the electronic noise is insignificant for the Inspector 2000. The fact that its resolution does not improve much as the shaping time increases is the characteristic of the Inspector 2000. This means that operation of the Inspector 2000 with these two detectors may be best at short shaping times (with high throughput) rather than long shaping times with low throughput and not much resolution improvement.

3. Comparison at high input count rate

Because the DSP systems perform very well at various input rates and shaping times, it is of interest to compare them at very high input rates with short shaping times. We acquired data with both detectors at input count rates of 100 and 150 kHz. We used shaping times of the DSP systems of 0.5, 0.7, 1.0, and 2.0 μ s for the planar detector, and 0.5, 0.7, 1.0, 1.4, and 2.0 μ s for the coaxial detector. Shaping times for the NIM system were 0.5, 1.0 and 2.0 μ s.

Figure 6 shows the results. The data at 100 kHz with shaping times greater than 2 μs are from section III.A.2. The throughput results are not shown here, but they are very similar to those in Figures 3, 4, and 5. That is, the throughputs of the three DSP systems are about the same while the throughput of the NIM system is much worse.



The resolution of the NIM system at low energy appears to be comparable to that of the DSP systems. Because of the aforementioned ballistic deficit effect with the coaxial detector at high energy, the performance of the NIM system is not good. The resolution of the NIM system at 1332 keV is very poor for 1- μs shaping and is washed out for 0.5- μs shaping. The performance of the Inspector 2000 is consistently better than that of the other three systems at

both 100 and 150 kHz and for all the shaping times tested, as shown in Figure 6, thus the Inspector 2000 is the choice for operation at high input rates.

4. Comparison with other spectroscopy systems

It is also of interest to compare these measurements with the archival measurements of other spectroscopy systems. References 1 and 2 compare ten systems using various detectors. One of those detectors is the same coaxial detector used in this evaluation. It is therefore appropriate to examine the results of other systems measured with this same coaxial detector. These are shown in Figures 7 and 8, taken from Reference 2, for the ten systems.

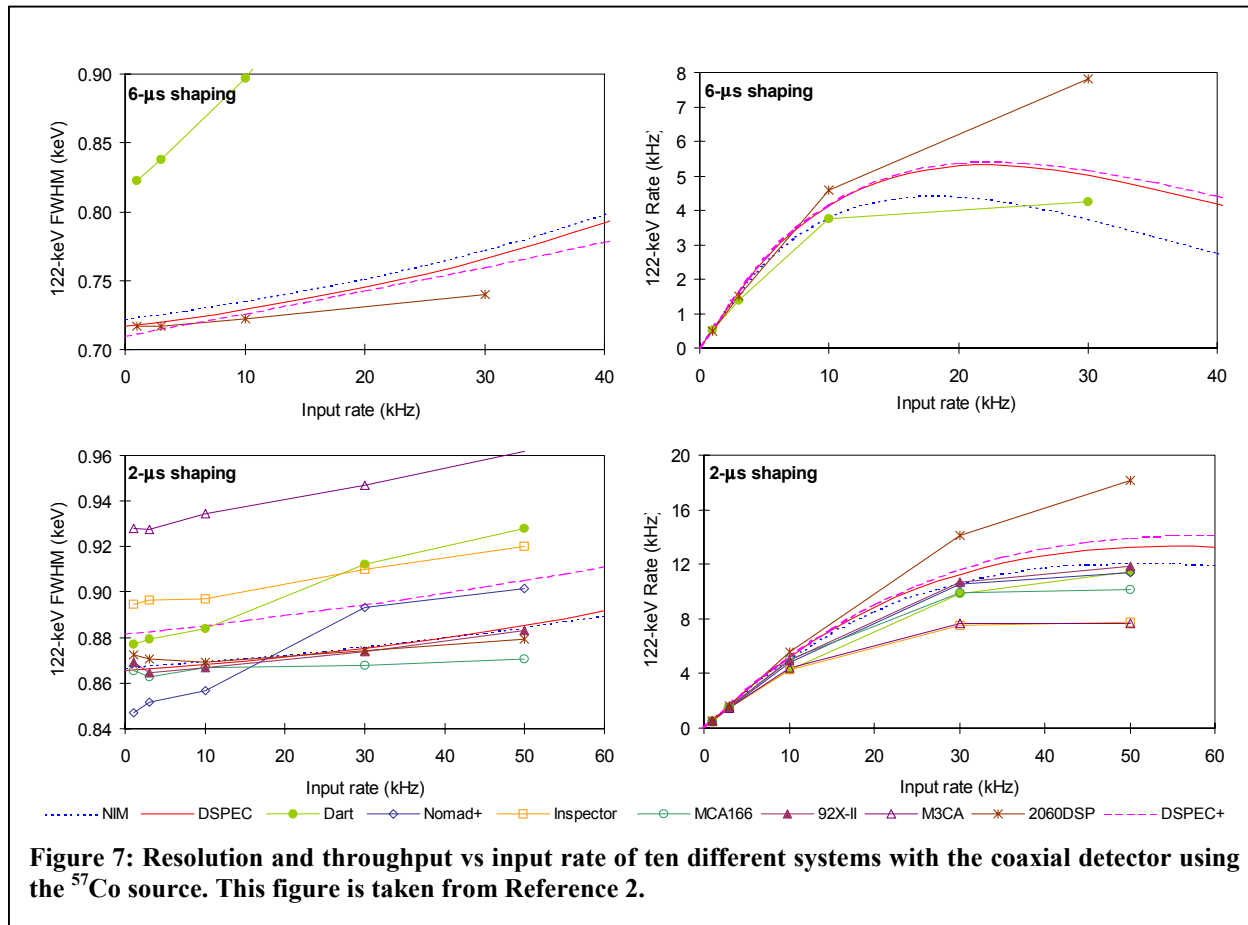
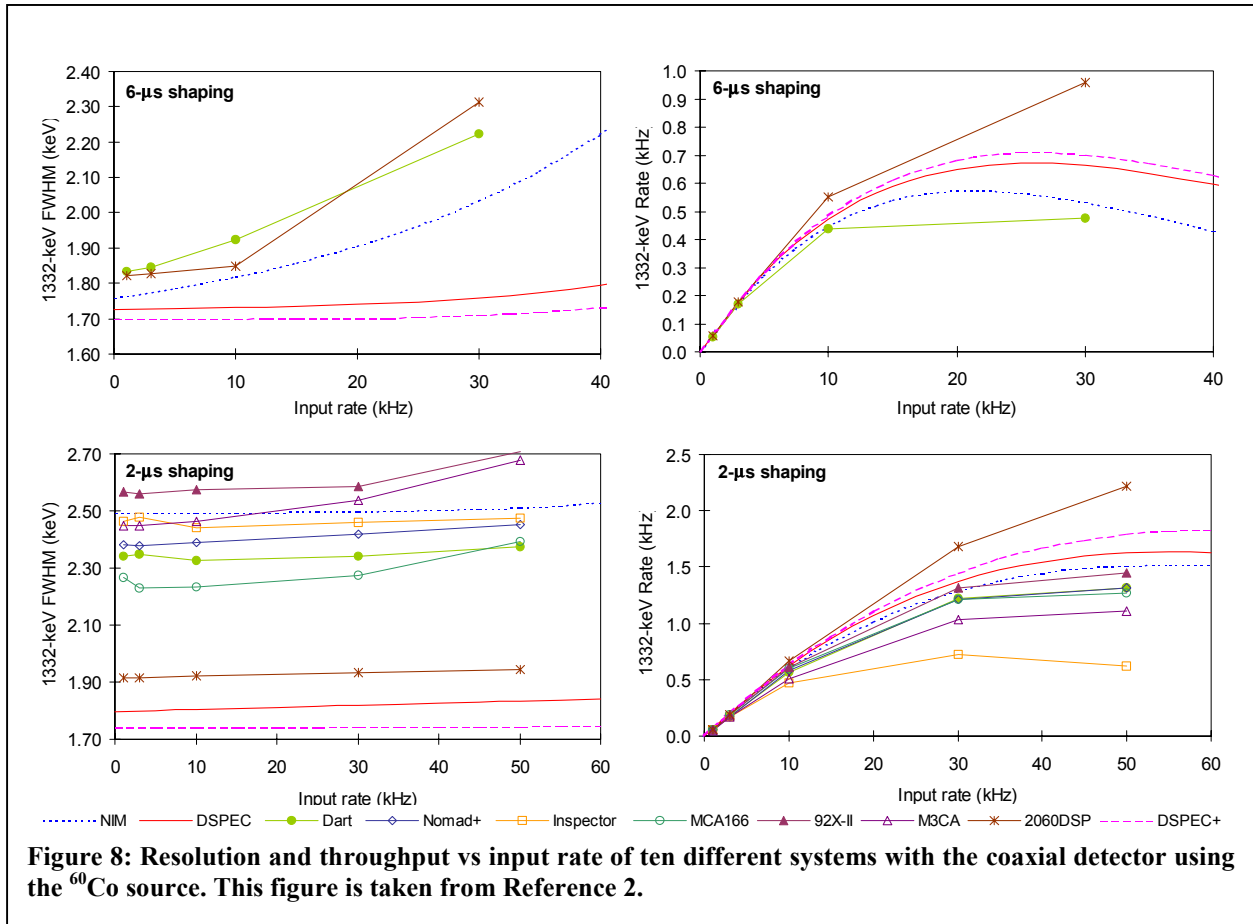


Figure 7: Resolution and throughput vs input rate of ten different systems with the coaxial detector using the ^{57}Co source. This figure is taken from Reference 2.

The three DSP systems used for these measurements are the DSPEC and DSPEC Plus from Ortec, and the 2060DSP from Canberra. The seven analog systems are the NIM with various modules from Ortec and Canberra, the Dart, Nomad Plus, and 92X-II from Ortec, the Inspector from Canberra, the MCA166 from GBS-Elektronik, and the M3CA from Aquila Technologies.



It is seen that the NIM appears to be the best of all the analog systems while the DSPEC or DSPEC Plus seems to be the best of all ten systems. Note the excellent performance of the DSP systems compared to the analog systems, especially at high energy with short shaping time. These data demonstrate that the DSP systems correct for the degraded performance and minimize the large ballistic deficit effect of this coaxial detector, resulting in much better resolution.

We conclude from these results (comparison of the NIM and three DSP systems in this paper and the comparison of the ten systems in References 1 and 2) that the performance of each tested DSP system is superior to that of any analog system.

B. Determination of best resolution and throughput performance

Depending on the application and the input count rate, one may choose the shaping/rise time of a system to optimize the resolution or throughput. We can estimate, from the empirical results shown in section III.A, the approximate shaping/rise time of each system for optimal performance at each different input rate. A more consistent approach would be a numerical evaluation of the best shaping time based on a simple mathematical equation or set of equations. We develop such an approach in this section.

1. Optimal resolution

Ignoring an abnormally large electronic noise (such as that of the NIM system), the resolution normally varies exponentially with input rate. The resolution may be described with the equation $a+b\exp(cF)$, where F is the input rate, and a , b , and c are some constants.

A plot of the above equation can represent the resolution at each shaping time. A set of curves, one for each shaping time, can be generated to represent a system with more than one shaping time. Figure 9 shows the set of three different resolution curves for the three different shaping times of a system running with a certain detector.

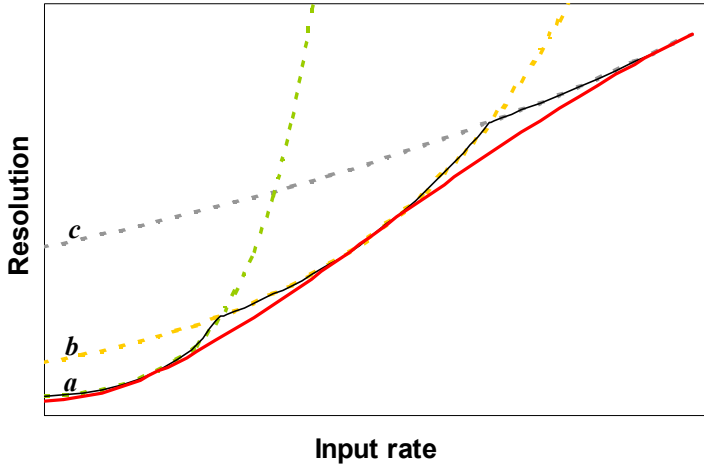


Figure 9: Dashed lines show a set of three different resolution curves for three different shaping times. Curve a represents a larger shaping time than curve b , and b represents a larger shaping time than c .

The shaping time of curve a is larger than that of curve b , which is larger than that of curve c . For a system with only these three shaping times, the thin solid curve represents the best resolution this system can achieve with this detector at all different input rate. For a system with continuous shaping time, that is, infinite shaping times that can be continuously adjusted for optimal resolution at different input rates, then its optimal resolution at all input rates can be represented by the thick solid curve.

The NIM system has only six widely separated shaping times

so its optimal resolution would resemble (with smaller breaks) that of the thin solid curve in Figure 9. Most other analog systems have only two shaping times (see References 1 and 2) so their optimal resolution curves would also be similar to that of the NIM, but with only one crossover point. Each DSP system, including the three used in this evaluation, has many rise times incremented in small steps. Although they are not continuous, the small steps make the rise time function appear almost continuous. The result is that the optimal resolution curve would be similar to the thick solid line in Figure 9.

A three-dimensional (3D) surface of the resolution as a function of the input rate and the rise time (or shaping time) is needed to determine the optimal resolution curve.

Using the results in section III.A, we found that the resolution behaves as $a_1+a_2T^{a_3}\exp(a_4T)$ (or $a_1+a_2\exp(a_3\ln(T)+a_4T)$ and $b_1+b_2\exp(b_3F)$ where T is the shaping time and F is the input count rate. The variable a_i is a function of F . That is, a_i is constant for fixed input rate F and varies as F changes. Similarly, the variable b_j is a function of shaping time T . Combining these two analytical forms gives the 3D surface formula:

$$\text{FWHM} = a+b\exp(c\ln(T)+dTF+eT+fF), \quad (1)$$

where T is the shaping time (for the NIM system) or rise time (for the DSP systems) in units of μs , F is the input count rate (kHz), and a , b , c , d , e , and f are constants. This equation is a simplified version of the much more complicated 2D formula. After some testing, we found that Equation 1 adequately describes the resolution behaviors of the systems. Because the results are not much different than those obtained with the more complicated formulae, we have used Equation 1.

All the resolution data (resolution, rise time, input rate) shown in section III.A are fitted to Equation 1 above. The data for each system are fitted separately. Figure 10 shows, as an example, the fitted resolution surface for the DSPEC Plus with the coaxial detector and the ^{57}Co source.

The optimal resolution curve is determined by setting the partial derivative of Equation 1 with respect to the rise or shaping time T equal to zero.

$$\partial(\text{FWHM})/\partial T = (c/T + dF + e) \text{bexp}(c \ln T + dTF + eT + fF) = 0.$$

This leads to

$$c/T + dF + e = 0, \tag{2}$$

which is the relationship between the rise/shaping time and input rate for optimal resolution. This curve, is shown as the thick line in Figure 10 for the DSPEC Plus with the coaxial detector and ^{57}Co source. It indicates that the optimal resolution for this system is at rise time of about $16 \mu\text{s}$ for a 30 kHz input rate, and as the rate increases up to 200 kHz , the optimal rise time drops to about $2.6 \mu\text{s}$.

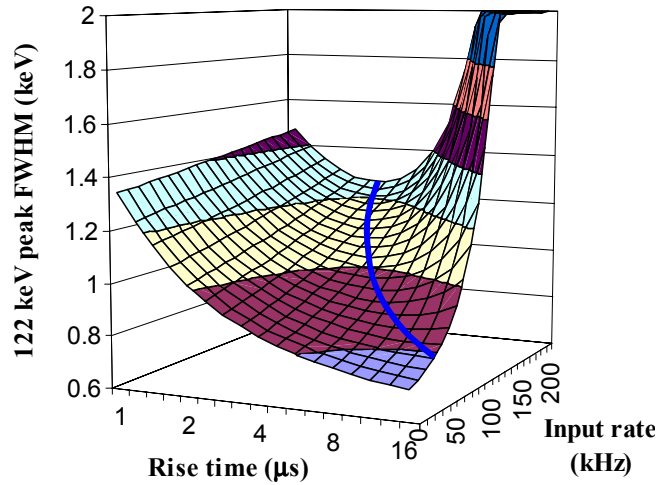


Figure 10: Fitted resolution surface for the DSPEC Plus with the coaxial detector and ^{57}Co source. The rise time scale is \log_2 . The thick line shows the optimal resolution at different input rates.

Table IV shows the constants obtained from the fits of the four systems for the two detectors and the two sources. One can use Equation 2 with these constants to determine the optimal shaping time or rise time (to achieve the best resolution results) for data acquisition at a given input rate. A smaller shaping or rise time may be substituted if the exact shaping or rise

time is not available. Note that the larger the shaping or rise time, the smaller the throughput. Trading off between resolution and throughput, one may use the smaller shaping time rather than the optimal one. A shaping time larger than the calculated optimal value should not be used because the resolution and throughput (section 2) are both worse (and at the shorter shaping time only resolution is worse) than the results at the optimal shaping time. Using the DSPEC Plus and the coaxial detector collecting data at low energy as an example, this means that the shaping time at various input rates should be set on or to the left of the optimal resolution curve (thick line in Figure 10) but not to the right of the curve.

Table IV. Constants from least-square fitting to the equation $FWHM = a + b \exp(c \ln(T) + dTF + eT + fF)$.

Detector	System	a	b	c	d	e	f
⁵⁷ Co Planar	DSPEC Plus	0.5126	0.1303	-2.001	0.00594	0.0000	-0.00339
	DigiDART	0.5089	0.1659	-1.200	0.00356	0.0000	-0.00352
	Inspector 2K	0.4687	0.0813	-1.397	0.00205	0.3383	0.00000
	NIM	0.5196	0.0203	-1.635	0.01215	0.0000	-0.00142
⁵⁷ Co Coaxial	DSPEC Plus	0.4083	1.0325	-0.691	0.00084	0.0405	-0.00130
	DigiDART	0.6860	0.7370	-1.111	0.00147	0.0601	-0.00154
	Inspector 2K	0.6683	0.8649	-1.505	0.00167	0.1199	-0.00278
	NIM	0.7835	0.1036	-3.286	0.00599	0.8716	-0.00284
	DSPEC Plus	1.5909	0.5723	-1.068	0.00341	0.0106	-0.00275
Coaxial	DigiDART	1.6532	0.6286	-1.212	0.00354	0.0247	-0.00309
⁶⁰ Co	Inspector 2K	1.5139	0.7337	-1.246	0.00182	0.1342	-0.00238
	NIM	1.6802	2.1769	-5.220	0.00960	1.0430	-0.01081

2. Optimal throughput

The optimal throughput for a system can also be determined in a similar fashion as that for the optimal resolution. Of course, the maximum throughput at all input rates is always obtained with the smallest available shaping or rise time of a system. However, a very small shaping time may compromise the resolution so that the system is unusable. The goal here is to determine the shaping times that can give good resolution and the best throughput at various input rates.

The throughput behavior at a fixed shaping time may be described with the equation $aF \exp(bF^c)$ where F is the input rate, and a , b , and c are some constants. A set of throughput curves, one for each shaping time, can be generated for a system with more than one shaping time. Figure 11 shows the three throughput curves that correspond to three different shaping times for a system running with a certain detector.

The bottom curve of the three dotted curves represents the largest shaping time, and the top curve, the smallest shaping time. The throughput rate is, of course, zero at zero input rate for each shaping time. As the input rate increases, the throughput also increases, up to a point. Then as the input rate keeps increasing, the throughput gradually decreases. The input rate corresponding to the maximum throughput for each shaping time is the optimal input rate.

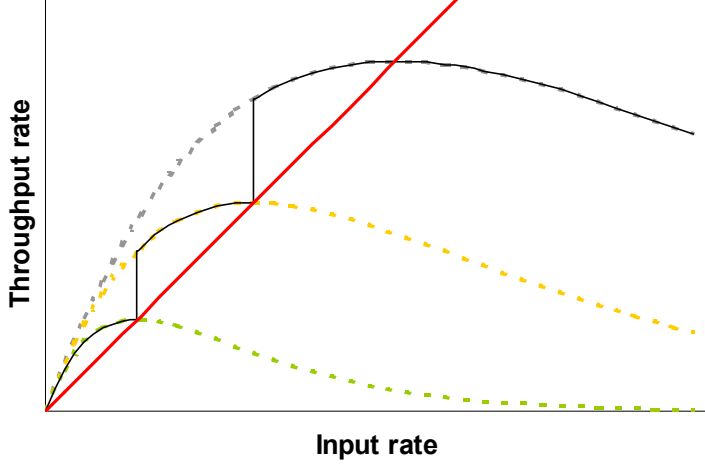


Figure 11: Set of three different throughput curves for three different shaping times.

We saw in the previous section, that for a typical system with a defined shaping time, the resolution is better at lower input rates. Considering the trade-off between the resolution and throughput, one may prefer to operate a system at some input count rate at or below that for optimal. As the input rate exceeds the optimal input rate, both throughput and resolution will suffer. It is best to maintain the input rate at or below the optimal for better performance. If reducing input rate to achieve this is not an option, one may try to reduce the shaping time to

raise the optimal input rate above the actual input rate, which is where the system should operate.

Note that the option of reducing the shaping time may not work for all the systems at all different shaping times. An example is the 2- μ s minimum shaping time for the NIM electronics with a coaxial detector. The resolution, especially at high energy, is so poor for this system with a 1- μ s shaping time, that there is no choice but to use the 2- μ s shaping time, even at count rates that greatly exceed the optimal input rate.

The thin solid line in Figure 11 shows the optimal throughput curve of a system with three different shaping times. The curve starts by following the curve with the largest shaping time. As it comes to the optimal input (maximum throughput) rate for that shaping time, it jumps to the next (lower shaping time) curve. When the count rate exceeds the maximum throughput (optimal input) rate for the smallest shaping time, the optimal throughput must follow the curve with the smallest shaping time beyond the input maximum. The optimal-throughput curve for the NIM or most other analog systems would be similar to this curve, with the number of jumps depending on the number of shaping time settings.

The thick solid curve in Figure 11 shows the optimal throughput for a system with continuous shaping or rise time. As mentioned in the last section, the rise times of the DSP systems are not continuous but can be considered so because of the very large number of rise times in the range. Therefore, the optimal curves of the DSP systems would be similar to this curve.

The optimal throughput curves for these systems are obtained by fitting the throughput data as a function of the input rate and the rise time (or shaping time) to a 3D surface. We found in section III.A that the throughput behaves as $a_1 \exp(a_2 T^{a_3})$ and $b_1 F \exp(b_2 F^{b_3})$ where T is the shaping time, F is the input count rate, a_i is a function of input rate F , and b_j is a function of shaping time T . Combining these two analytical forms gives the simplified 3D surface formula:

$$\text{Throughput} = a F \exp(b T^c F^d), \quad (3)$$

where T is the shaping time (for the NIM system) or rise time (for the DSP systems) in units of μs , F is the input count rate (kHz), and a , b , c , and d are constants.

The data (throughput, shaping time, input rate) for each system are fitted separately. Figure 12 shows, as an example, the fitted throughput surface for the DSPEC Plus with the coaxial detector and the ^{57}Co source.

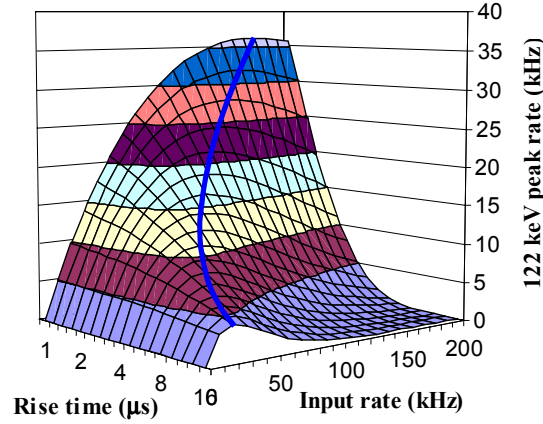


Figure 12: Fitted throughput surface for the DSPEC Plus with the coaxial detector and ^{57}Co source. The rise time scale is \log_2 . The thick line shows the optimal throughput at different input rates.

The optimal throughput is determined by setting the partial derivative of Equation 3 with respect to the input rate F equal to zero, as follows:

$$\frac{\partial(\text{Throughput})}{\partial F} = a \exp(bT^c F^d) + abdT^c F^d \exp(bT^c F^d) = 0 .$$

This leads to

$$bdT^c F^d = -1 . \tag{4}$$

Substituting Equation 4 back into Equation 3 gives

$$\text{Throughput} = aF \exp(-1/d). \tag{5}$$

Equation 5 represents the optimal throughput curve of a system, and it turns out to be linear with the input rate, as illustrated in Figure 11. It is derived from the thick line on top of the ridge in Figure 12.

Table V shows the constants obtained from the fits of the four systems for the two detectors and the two sources. One can use Equation 4 with these constants to determine, for data acquired at a defined input rate, the shaping time or rise time of a system for best throughput results. A smaller shaping or rise time may be substituted if the exact shaping or rise time is not available. Similar to the case in which resolution is optimized, a shaping time larger than the calculated optimal value should not be used because resolution and throughput are worse (and at the shorter shaping time only resolution is worse) than the results at the optimal shaping time. This means that for a 3D throughput surface like the one in Figure 12, the shaping/rise time for

Table V. Constants from least-square fitting to the equation $\text{Throughput} = aF\exp(bT^cF^d)$

Det.	System	a	b	c	d
⁵⁷ Co	Planar DSPEC Plus	0.6301	-0.00550	0.7461	0.9985
	Planar DigiDART	0.6036	-0.00467	0.8119	0.9970
	Planar Inspector 2K	0.5618	-0.00139	1.0092	1.2212
	Planar NIM	0.5808	-0.00885	0.8055	1.0370
⁵⁷ Co	Coax. DSPEC Plus	0.5007	-0.00295	0.8034	1.1192
	Coax. DigiDART	0.5211	-0.00191	0.9393	1.1629
	Coax. Inspector 2K	0.5459	-0.00171	0.9206	1.1315
	Coax. NIM	0.5552	-0.01488	0.7597	0.9569
⁶⁰ Co	Coax. DSPEC Plus	0.0592	-0.00181	0.8470	1.1934
	Coax. DigiDART	0.0594	-0.00070	1.0195	1.3320
	Coax. Inspector 2K	0.0577	-0.00029	1.0543	1.4339
	Coax. NIM	0.0717	-0.01281	0.8282	0.9730

different input rates should be set on or to the left of the optimal throughput curve (thick line in Figure 12) and not to the right of the curve.

3. Optimal resolution and throughput performance

We have determined the optimal resolution and optimal throughput of the systems as functions of shaping/rise time and input rate in sections 1 and 2. Both of those determinations suggest that the shaping/rise time should not be set larger than that corresponding to the optimal resolution or throughput

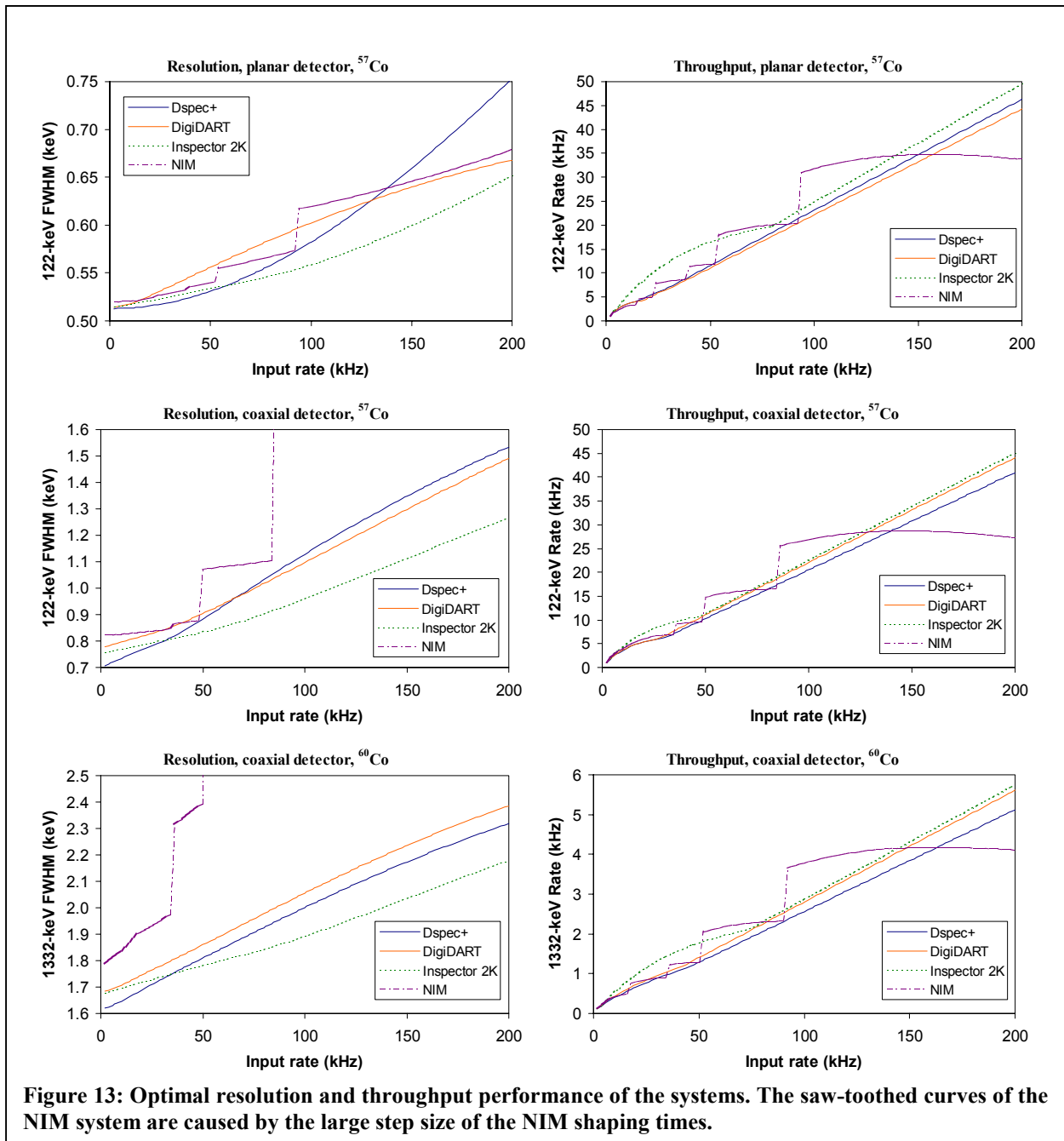
because of the trade-off between resolution and throughput. We can now combine these two constraints to obtain the optimal resolution and throughput performance that these systems can achieve.

Equations 2 and 4 give the shaping/rise time as a function of input rate for optimal resolution and throughput, respectively. These two equations are then compared with each other at each input rate, and the one with smaller shaping/rise time value is chosen. In general, optimal performance at low input rates is determined by the optimal resolution curve, and at high input rates it is determined by the optimal throughput curve.

Figure 13 shows the optimal resolution and throughput performance results. The performance curves of the NIM system are saw-toothed because of the discrete, large-step shaping times. The curves of the DSP systems are also saw-toothed, but the behavior is much less prominent because the discrete shaping times are numerous and closely spaced. For simplicity of plotting, the curves for the DSP systems shown in Figure 13 are plotted as smooth curves.

Examining the performance curves for the DSP systems carefully, it appears that they are not perfectly smooth. A kink appears in each curve, and this is clearest for the throughput curves of the Inspector 2000. The kinks correspond to the switchover from the optimal resolution performance to optimal throughput performance. The switchover occurs at about the same input rate for the DSPEC Plus and the DigiDART and at about twice that input rate for the Inspector 2000.

The results for the NIM system are somewhat surprising. Figures 3, 4, and 5 show that the throughput of the NIM system is always worse than that of the DSP systems when resolution is optimized. However, Figure 13 shows that for most of the input rate range from 0 to 150 kHz, the NIM throughput is comparable to or even better than that of the DSPEC Plus and the DigiDART. The improvement in throughput comes at the price of poorer resolution. Figure 3



shows that the resolution of the NIM system for the planar detector is about the same as that of the DSPEC Plus at all input rates and shaping times while the throughput is much worse. Figure 13 illustrates the tradeoffs inherent in optimizing the overall performance—the throughput of the NIM is somewhat better and the resolution is worse than that of the DSPEC Plus. The poor resolution of the NIM with the coaxial detector and ^{57}Co source, at the lowest shaping time, $0.5\ \mu\text{s}$, makes it unusable at this setting. Similarly with the ^{60}Co source, the resolution at a shaping time of $1.0\ \mu\text{s}$ is also of virtually no use. Thus, for general data acquisition, where many different gamma ray peaks at different energies are recorded, the smallest shaping time that the NIM system can effectively use with this coaxial detector is $2\ \mu\text{s}$. The throughput for this minimum

shaping time peaks at about 50 kHz input rate for both the ^{57}Co and ^{60}Co sources. This corresponds to the maximum total throughput of about 16 kHz. The throughput for input rates greater than 50 kHz will be reduced and the resolution will be worse. The input rate for this NIM system/coaxial detector combination should not exceed 50 kHz.

The NIM system performs well with the planar detector, even at the smallest shaping time, 0.5 μs . The resolution for this combination with performance optimized is comparable to that of the DigiDART, and the throughput is even better than that of the DigiDART and DSPEC Plus.

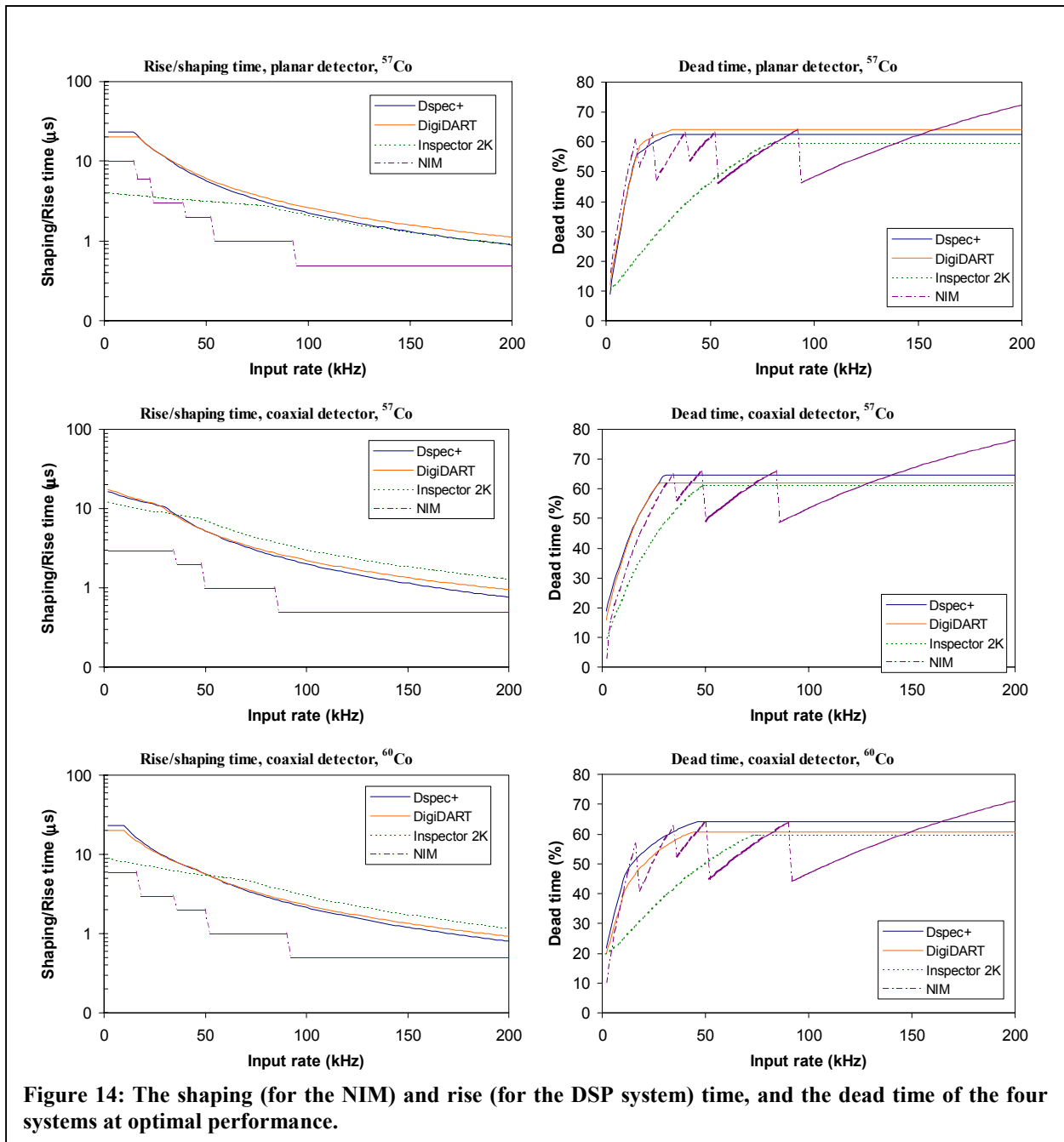
The three DSP systems with performance optimized have similar throughput rates, except for low input rates where the Inspector 2000 throughput rate is somewhat better. This is because the switchover (from optimal resolution to optimal throughput) of the Inspector 2000 occurs at a much higher input rate than that of the DigiDART and DSPEC Plus. When the input rate is below the switchover input rate, the rise time is best for optimal resolution and is smaller than the rise time for optimal throughput. Therefore, the throughput is larger. It is interesting to note that at high input rates, the optimal performance would be that of the optimal throughput, and the throughputs of all three systems are very much the same, with the throughput of the Inspector 2000 slightly better than that of the other two.

The resolution of the Inspector 2000 at optimal performance is better than that of the DigiDART at all input rates for both detectors and sources. Compared with the DSPEC Plus, the resolution of Inspector 2000 is somewhat worse at small input rates and somewhat better at large input rates than that of the DSPEC Plus.

Overall, the DSP systems appear to be excellent. Their performance with the coaxial detector is much better than that of the NIM, which means better than most if not all the analog systems. The throughput rates for these three systems are also excellent. The throughput graphs show that at 200 kHz input rate, the total throughput rate for each DSP system is about 70 kHz. We only took data at input rates up to 150 kHz. The extrapolation up to 200 kHz input rate may still be reasonable, but beyond that, it may not be very accurate. However, we believe that with these DSP systems, the throughput rate of 100 kHz, with an input rate of 300 kHz is achievable.

The NIM, DSPEC Plus, and DigiDART have count-rate meters to measure the input rate, but the Inspector 2000 does not. The count-rate meter is useful in determining the rise time for optimal performance. However, all three DSP instruments have the dead-time meter, which can be used in the determining the optimal shaping/rise time.

The shaping/rise times and input rates corresponding to optimal performance for the four systems determine the optimal dead times for these systems. Figure 14 shows the optimal shaping/rise times and dead times of the four systems. The vertical scales on the shaping/rise time plots correspond to shaping time for the NIM and rise time for the DSP systems. Also on these shaping/rise time plots, the flat rise time of the DSPEC Plus and DigiDART at small input rate is the maximum rise time of each of these systems.



The dead time for all the systems in Figure 14 starts at zero for zero input rate and sharply increases as the input rate increases until the switchover point. Then it becomes flat. That is, with the optimal performance, the dead time increases with the input rate. When the input rate passes the switchover rate, the optimal performance is now the optimal throughput performance, for which dead time is constant for all the input rates. The average dead time with both detectors and sources at high input rate is about 63% for the DSPEC Plus and DigiDART and 60% for the Inspector 2000. The abrupt changes in the shaping times cause the NIM dead-time curves to be saw-toothed, varying from about 45% to 65%. Note that the tops of the teeth of the NIM curves are all at about the same height, 65%.

The optimal throughput equation (Eq. 5) predicts that the dead-time curve at high input rate would be completely flat. That is

Dead time = 1 – Live time = 1 – Throughput/Input = 1 – $a \exp(-1/d)$ = constant, where a and d are variables determined from fitting Equation 3 and are displayed in Table V.

This is indeed what we observe in Figure 14. The dead-time curves in this figure do not come from the actual, observed dead times of the systems. They are generated from the equation Dead time = 1 – Live time = 1 – Throughput/Input. These dead times are almost but not quite the same as the observed dead times. The differences are due to imperfect rate-loss (due to dead time and PUR) correction electronic circuits. (The accuracy of the rate-loss correction for each system is determined in a later section.) The differences between the calculated dead times and the observed dead times are small in the range of dead times, below 65% as indicated in Figure 14, for optimal performance. Therefore, either the dead-time indicator or count-rate meter of a system can be used in setting up to determine optimal performance.

Because of the trade-offs between resolution and throughput, one may operate a system with the shaping/rise time or the dead time smaller than the curves in Figure 14. A simple rule of thumb is that under no circumstance should the dead time be allowed to exceed 60% (unless the system is the NIM running with the coaxial detector at its smallest useful shaping time of 2 μ s). If the dead time exceeds 60%, then reducing the shaping/rise time slightly to decrease dead time to below that level would enhance the throughput and perhaps the resolution as well.

C. Peak stability

It is of interest to study the peak stability of these systems as a function of input count rate and as the long-term drift influenced by gradual changes in ambient temperature over time. Table VI shows the stability specifications of the three systems. The NIM system uses both the Ortec 672 amplifier and the Canberra 8706 ADC. Therefore, the stability of the NIM equals the quadratic sum of the stability for these two modules. The “peak shift” (as function of input rate) is specified for input rates up to 100 kHz. The DSP systems do not specify peak shift values. The “zero shift” of the NIM is stated for the amplifier as 7.5 μ V/ $^{\circ}$ C. The value in the table is converted to percent per degree Celsius, assuming that the amplifier gain is about ten and the full voltage output is 10 V. All three DSP systems specify the gain- and zero-shift as parts-per-million per degree Celsius (ppm/ $^{\circ}$ C), and these have been converted to percent per degree Celsius in Table VI for easy visualization.

1. Peak position as function of input count rate

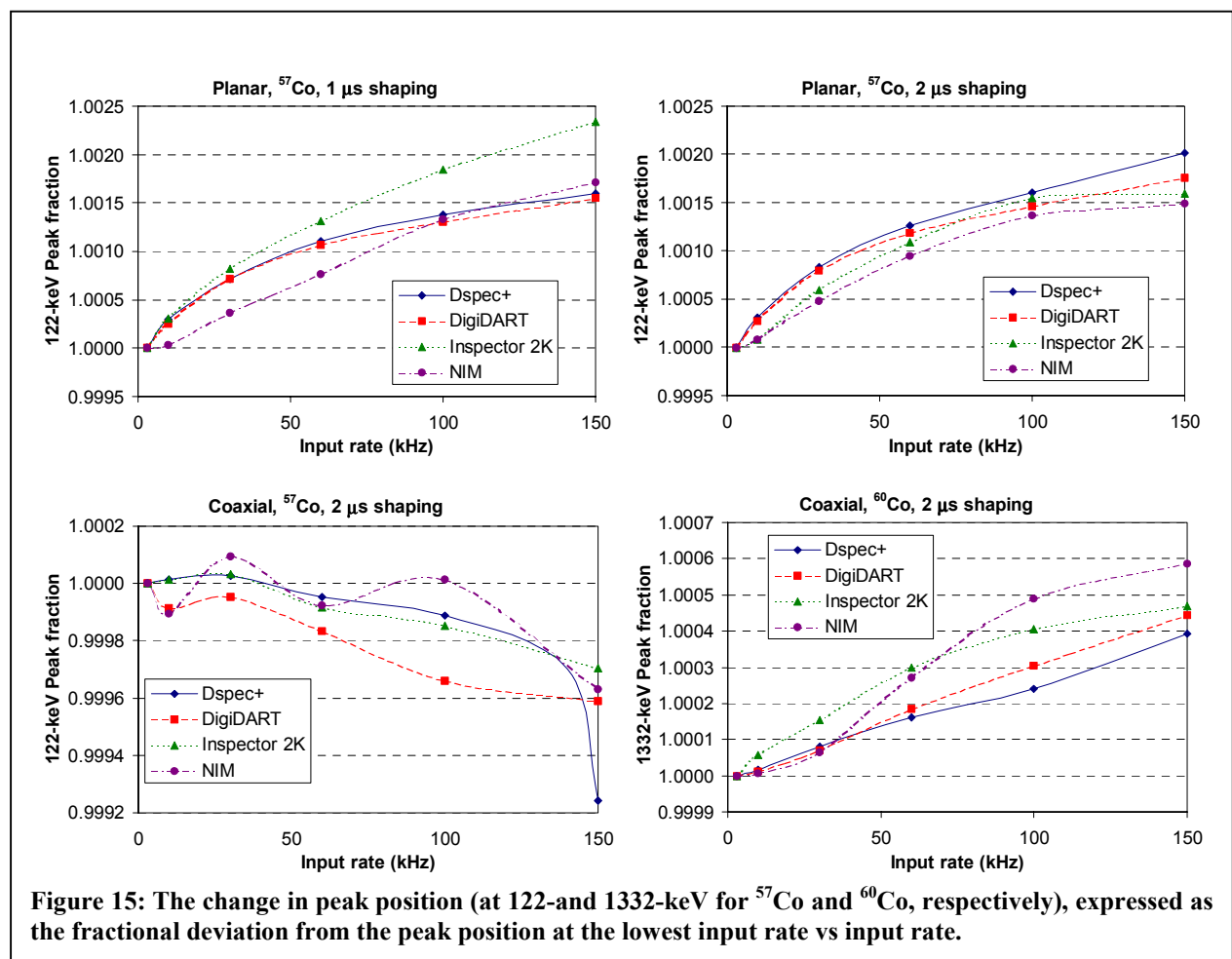
The acquired data specified in section III.A includes all the data taken at various shaping times and input rates. The range of input rates for the planar detector with 1- and 2- μ s shaping

Table VI. Specifications for the peak stability of the three systems.

Stability	Ortec 672 Amplifier	Canberra 8706 ADC	NIM	DSPEC Plus	DigiDART	Inspector 2000
Peak shift (%)	<0.018	<0.025	<0.03	N/A	N/A	N/A
Gain shift (%/ $^{\circ}$ C)	<0.005	<0.009	<0.01	<0.005	<0.005	<0.0035
Zero shift (%/ $^{\circ}$ C)	<0.0008	<0.0025	<0.0026	<0.001	<0.001	<0.0003

times was 3 to 150 kHz. The input range for data taken at other shaping times is smaller. The range of input rates for the coaxial detector at only the 2- μ s shaping time was 3 to 150 kHz. Data obtained with the planar detector using 1- and 2- μ s shaping times and coaxial detector using 2- μ s shaping time are used for the determination of the peak shift as function of input rate.

Figure 15 shows the variation of the positions of the 122- and 1332-keV peaks as the fractional deviation from the peak position at the lowest rate. Ignoring two exceptions (the Inspector 2000 with the planar detector at 1- μ s shaping time and the DSPEC Plus with the coaxial detector and the ^{57}Co source), the overall performances of all the systems are about the same.



The peak position with DSPEC Plus using the coaxial detector and ^{57}Co source changes dramatically from the 100 kHz to the 150 kHz input rate. Further testing shows that at 140 kHz, the change in peak position is still small (on the graph in Figure 15, the measured value at 140 kHz is 0.9997) but becomes exponentially large for larger input rate. Operation of both the rise time and the coarse gain functions contribute to this problem.

It appears that the DSPEC Plus uses two different electronic circuits for the rise time, one for rise times from 0.2 to 3.0 μ s and one for rise times from 3.2 to 23.0 μ s. One can hear the clicking sound when the rise time is changed from 3.0 to 3.2 μ s or vice versa. No sound is heard

when the rise time is changed between settings within one range or the other. When a rise time of $\leq 3.0 \mu\text{s}$ is used, the peaks shift gradually as the input rate changes (up to $>300 \text{ kHz}$). If a rise time of $\geq 3.2 \mu\text{s}$ is used, then at an input rate of about 140 kHz , the peaks start to shift dramatically and the resolution also worsens in proportion to the peak shift.

This problem should not affect the normal operation of the DSPEC Plus at all. Actual operation at very high count rates requires that the rise time be set at a much smaller value than $3.2 \mu\text{s}$ to reduce dead time. Figure 14 illustrates that for input rates above 100 kHz , the rise time for the DSPEC Plus should be set at or below $2.2 \mu\text{s}$. Therefore, the problem of dramatical peak shifts at very high input rates and large rise time should not occur under normal operation.

Another operation that contributes to the large peak shift is the coarse gain. The total gain of the DSPEC Plus was about 10 with the coaxial detector using the ^{57}Co source in order to position the 122-keV peak at channel 3200 out of 4K channels. The acquisition that produced the data in Figure 15 used a coarse gain of 20 and a fine gain of ~ 0.5 . When the same total gain is achieved with settings of 10 and 1.0 for the coarse and fine gains, respectively (so that the peaks would still be in about the same positions), the peak position does not shift much until the input rate exceeds 180 kHz .

We think that the circuits for the $\times 20$ and larger coarse gain are noisier than those for the $\times 10$ or smaller coarse gain. When the coarse gain is set at 10 or less, regardless of the fine gain setting or the input rate, the count rate meter of the DSPEC Plus shows a rate about 94% of that when the coarse gain is set at 20 or larger. The lower count rate (observed at coarse-gain settings of 10 or less) agrees with the count rate from the NIM system, which leads us to believe that the count rate shown for $\times 20$ coarse gain or larger is 6% too large. This problem is not caused by noise from the detector or the preamplifier because—if it were—a higher coarse gain would amplify the noise even more, and the rate shown in the count-rate meter would increase proportionally with the amplifier gain. This is not what we observed. We believe that the amplifier circuit with the $\times 20$ or larger coarse gain somehow introduces electronic noise into the system that is above the discriminator of the count-rate meter, and the amount of noise is proportional to the input rate.

The effect of the 6% noise on the system is a very small decrease in throughput. The throughput at high count rate (greater than 100 kHz) when the coarse gain is at 20 or larger is only about 1% less than when the coarse gain is at 10 or less, and both throughputs are essentially the same at low count rate.

Since the DSP systems do not have a specification for the peak shift as function of input count rate, we cannot readily say if their results in Figure 15 are good or not. However, their peak shifts are about the same as that of the NIM system ($\sim 0.15\%$ for the planar and 0.05% for the coaxial detectors). These are very much larger than the specified value of 0.03% for the NIM system. The reason for this apparent unsatisfactory performance (observed vs specified peak shift for NIM) is mainly a result of the imperfect detector and preamplifier systems and not the MCA systems.

Note the trends in each graph in Figure 15 for these systems. They are all very similar. This means that the detectors and preamplifiers and not the MCA systems cause most of the peak shift.

2. Peak position as function of time

The coaxial detector and the combination of ^{57}Co and ^{60}Co were used to determine the shifting of the peaks. No stabilizers were used to stabilize the peaks. The systems were set up to collect and store the data every 30 minutes. The data for each system were acquired separately and, for each system, 48 spectra were recorded over a 24-hour period. The data were acquired in consecutive 24-hour periods. When the data acquisition for one system was complete, another system was set up to acquire data using the same detector and sources. The start times for the 24-hour acquisitions were between 5 and 6 PM.

The changes in positions of the 122- and 1332-keV peaks are recorded as the fractional variation from the average, obtained by dividing the peak positions for the individual spectra by the average for the 48 spectra. Figure 16 shows this relative peak positions vs time. The temperature in the room in which the experiment was running changed by less than $3\text{ }^{\circ}\text{C}$ in one day during the 24-hour period of data acquisition. This estimate combined with the gain stability specification for each instrument (Table VI) determines the specification for the long-term shift.

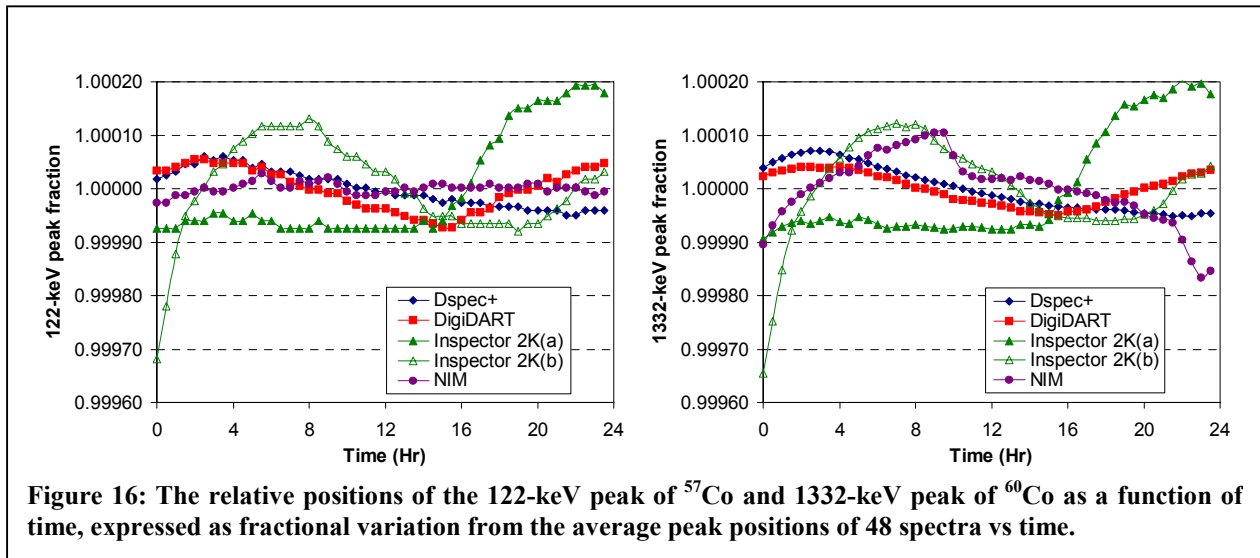


Figure 16: The relative positions of the 122-keV peak of ^{57}Co and 1332-keV peak of ^{60}Co as a function of time, expressed as fractional variation from the average peak positions of 48 spectra vs time.

The Inspector 2000 has two different sets of data points representing the peak shift as function of time. The first set (a) was taken in the same week in which the data for the other system were acquired. A few months later, we analyzed these data and found the somewhat unusual behavior of the Inspector 2000. Suspecting bad measurements for the first data set, we acquired the data for the Inspector 2000 again using the same detector and source. The starting time for this data set was also between 5 PM and 6 PM. The second data set (b) is even worse than the first one. Note the similarities and differences between the two sets of data. The time intervals in which the peaks shifted quickly were about 6 hours for both data sets. The dramatic shifts occurred between the 15th and 21st hr (8:30 AM to 1:30 PM) for (a). The quick shift for (b) started right after turning on the system at about 5 PM, with relatively stable operation beginning at about 11 PM. The total magnitudes of the (b) shifts are about 1.5 times larger than those of the (a) shifts. Overall, the total peak shifts measured from these two data sets are about 0.03% and 0.05%, which are well above the specification limit for the Inspector 2000.

Note that if the (b) acquisition for the Inspector 2000 started two hours later or if the first four data points are removed, then the (b) results for the Inspector 2000 would be comparable to or only slightly worse than those of the other three systems.

The NIM system appears to give the smallest total peak shift at 122 keV (only 0.006%) over a period of 24 hours. This long-term peak shift for the NIM system is worse at 1332 keV (almost 0.03%), although this is still within the specification limit for the NIM. The peak shifts of the DSPEC Plus and the DigiDART are similar, at about 0.012% for both the low- and high-energy peaks. The peak-shift performances of these three systems appear to be within their specifications as shown in Table VI.

During a long period of data acquisition, how much would these peak shifts hurt the resolution of each system? The 48 spectra of each system are summed together to form a spectrum with a total acquisition time of exactly one day. The resolution of each of the two peaks in each 24-hour sum spectrum is compared to that in the half-hour spectrum. Table VII shows the resolution of the peaks in the sum spectra and the averages and standard deviations of the peaks in the 48 individual spectra. The DSPEC Plus, DigiDART, and NIM systems show the same resolution for the peaks in the 24-hour sum spectrum as for the peaks in the 30-minute spectra. Note that differences between the resolutions of the sum spectra and the average resolutions are well within their respective standard deviations. Thus, for these three systems operating with long acquisition times, the long-term peak shift would not have any effect on the resolution of the systems.

Table VII. The effect of the acquisition time on the resolution of the system. The values are for the FWHM in units of keV. “Sum” represents the 24-hour sum spectrum. “Ave.” and “STD.” represent the average peak resolution and standard deviation of the 48 individual spectra, respectively.

	DSPEC Plus		DigiDART		Inspector 2K(a)		Inspector 2K(b)		NIM	
	122-keV	1332-keV	122-keV	1332-keV	122-keV	1332-keV	122-keV	1332-keV	122-keV	1332-keV
Sum	0.9408	1.7390	0.9596	1.7859	0.9242	1.7733	0.9089	1.7613	0.9354	2.3645
Ave.	0.9404	1.7358	0.9603	1.7849	0.9237	1.7422	0.9075	1.7380	0.9353	2.3577
STD.	0.0020	0.0141	0.0015	0.0053	0.0013	0.0040	0.0034	0.0054	0.0071	0.0083

Despite expectations derived from the curves in Figure 16 for the Inspector 2000, the resolution degradation of the 24-hour spectrum is insignificant for the 122-keV peak and about 1.5% for the 1332-keV peak, which is also not very large.

Note that all these systems have both gain and offset stabilizers. Actual measurements that require a long counting time in an environment with significant fluctuations in the ambient temperature would probably use the stabilizers, and the resolution degradation would be eliminated.

D. Linearity

All four systems are expected to be highly linear over most of their dynamic range. It is of interest to measure the nonlinearities of these systems. The maximum ranges of these systems

are 16K channels. Table VIII shows the specified nonlinearities of these systems. The values for the NIM system are the combinations of both the amplifier and the ADC.

Table VIII. Nonlinearity specifications of the systems.

	Ortec 672 Amplifier	Canberra 8077 ADC	NIM	DSPEC Plus	DigiDAR T	Inspector 2000
Integral nonlinearity (%)	<0.025	<0.025	<0.035	<0.025	<0.025	<0.025
Differential nonlinearity (%)	N/A	<0.7	<0.7	<1	<1	<1

1. Integral nonlinearity

Integral nonlinearity refers to the deviation from the straight line representing the relationship between input pulse height (or energy) and the output spectrum channel. Inputs of accurately known amplitudes sent to the system are plotted against the output channel assigned by the system to test the integral nonlinearity of a system. The maximum deviation of the data points over the whole range of channels from a straight line fitted to the points is the integral nonlinearity.

The input signal can be from any source. We have used a precision pulser and the germanium coaxial detector. Note that when a system is tested with the pulser the nonlinearity of that system also includes the nonlinearity of the pulser, and when it is tested with the germanium detector its nonlinearity also includes those of the detector, the preamplifier, and the inaccuracies of the peak energies of the sources.

a) Test with the precision pulser

The four systems were tested using the Ortec model 448 pulser. The 2- μ s shaping time was used for all three systems. Figure 17 shows the results.

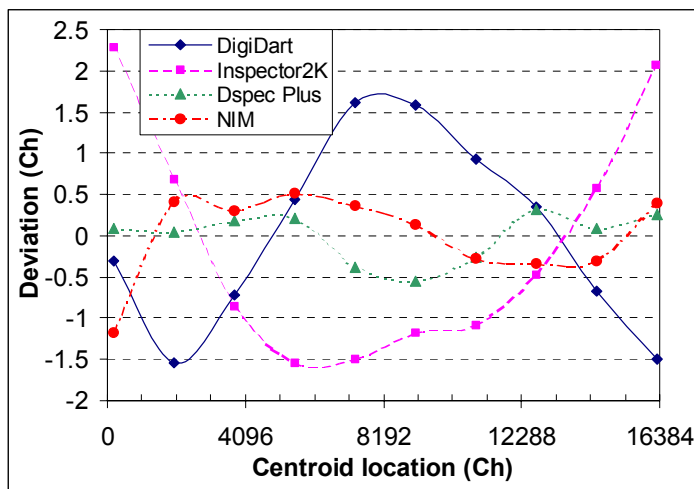


Figure 17: Results of the integral nonlinearity tests using the pulser.

The results for the DSPEC Plus are excellent. Except for a point at very near channel zero, the NIM system is also excellent. The DigiDART and Inspector 2000 are not as good compared with the other two systems.

b) Test with the germanium detector

The systems were also tested with the germanium coaxial detector. It is perhaps a better test than the test with the pulser because, after all, it tests the linearity of the entire system (including detector, preamplifier, amplifier, and ADC). The ^{133}Ba

and ^{152}Eu sources provide many gamma rays ranging from 53 keV up to 1408 keV to cover most of the 16K-channel range of the systems. Figure 18 shows the results for all four systems.

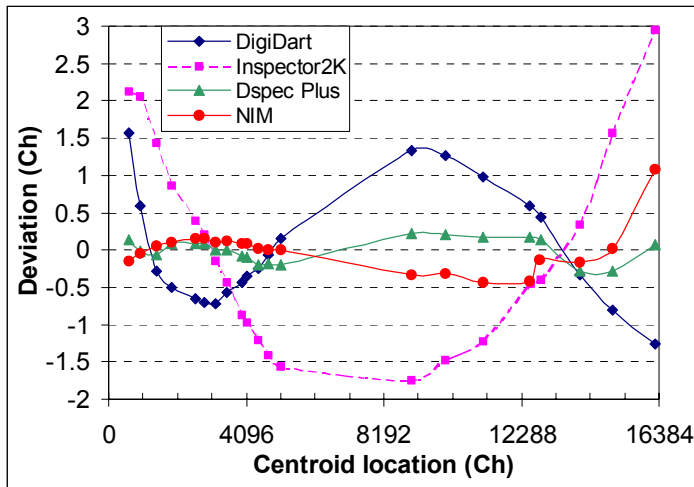


Figure 18: Results of the integral nonlinearity tests using the coaxial germanium detector and the ^{133}Ba and ^{152}Eu sources.

Again, the DSPEC Plus and the NIM (except for the point at the highest channel) perform excellently while the DigiDART and Inspector 2000 are not as good. Although the Figure 18 shows that the maximum deviations for the DigiDART and Inspector 2000 are about 0.01% to 0.015%, which are less than the specifications of 0.025%, we still think that they are unsatisfactory.

Note that, for the Inspector 2000, the curves in both tests (with the pulser and the HPGe detector) have a V shape with the pointed end at about the midpoint of the 16K-channel range. When we

tested only 8K-channel range, we also see a comparable V shape. It appears that the ADC (or its equivalent) of the Inspector 2000 consists of four different 4K-blocks. The need to combine blocks may contribute to the large integral nonlinearity.

2. Differential nonlinearity

Differential nonlinearity (DNL) is a measure of the equality of channel widths in an MCA system. A perfectly flat spectrum of random pulses presented to a perfect ADC with no differential nonlinearity would produce the same number of counts in every channel within the statistical uncertainty of the channel counts. We do not have a source that can provide a perfectly flat spectrum of random pulses, so we use an imperfect but acceptable source to provide the pulses for this test.

A 2.5-cm diameter by 2.5-cm thick NaI detector was used with the ^{137}Cs source to provide a smooth spectrum for the test of differential nonlinearity. Only the Compton continuum was included in the spectrum. The input rate was about 110 kHz. The signal was split into four inputs to the four systems. The rise times of the DSP system were set at 0.8 μs , and the shaping time of the NIM was set at 0.5 μs .

The data were continuously acquired for a total of six days (500,000 seconds), giving the three DSP systems more than 1 million counts per channel for most of the 16-K channel range. The larger dead time of the NIM system causes its counts per channel to be only about half that of the DSP systems. The statistical uncertainty of each channel is $\sim 0.1\%$ or less for the DSP system and $\sim 0.14\%$ or less for the NIM system, more than sufficient for the test, in that the differential nonlinearity specifications of these systems are much larger (see Table VIII).

Figure 19 shows the spectra of the four systems. It is impossible to see any DNL in these systems with the scale in Figure 19. Therefore, these spectra have been subtracted from their respective smoothed spectra.

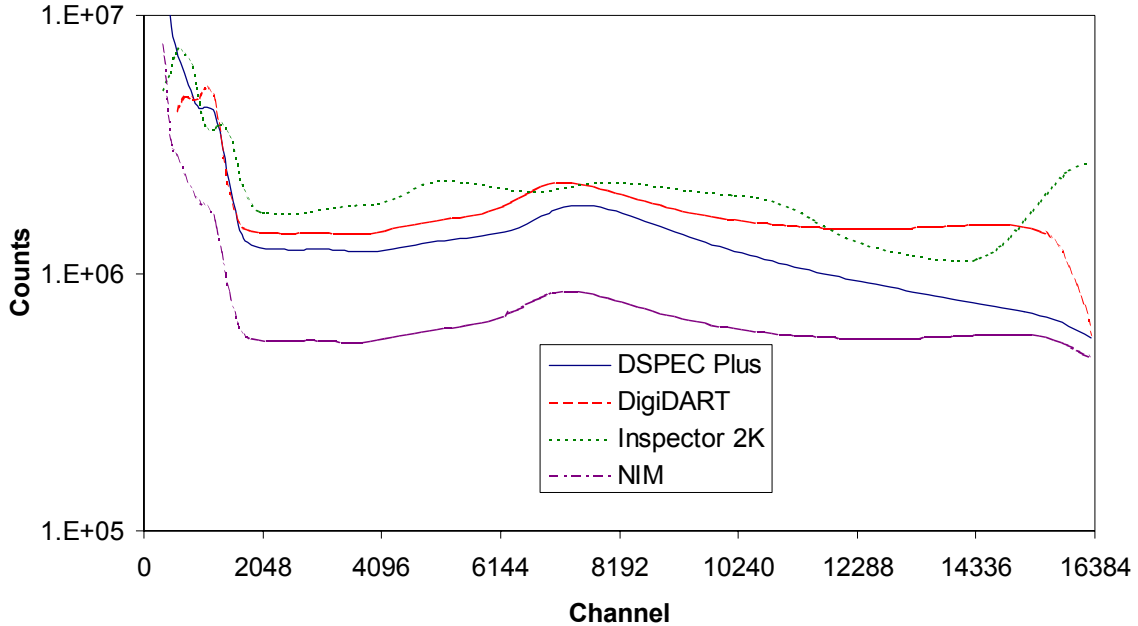


Figure 19: Spectra of the four systems obtained with the NaI detector and ^{137}Cs source.

The smoothed spectra were obtained by smoothing the data using the 51-point cubic fit. That is, for each point on a spectrum, a cubic is fitted through 51 data points centered on that point (25 points below and 25 points above). The smoothed data point is the centered point of those used in the fit. The smoothed spectra were examined for the structures that might arise from the smoothing, but none were observed.

Figure 20 shows the difference (between the “raw” and “smoothed”) spectra. The smooth-line represents the ± 3 -sigma statistical uncertainty of each set of difference.

Very few of the points for the DSP systems (consistent with statistics, which would predict about 40 points out of 16,000) fall outside the 3-sigma range. This means that most of the deviations come from statistics and not the DNL. The channel range above about channel 2000 appears to be consistent with statistics for the NIM system, but the range below it shows many points exceeding the 3-sigma limit. Nonetheless, the NIM results still correspond to a DNL of $\leq 0.3\%$, which is still much better than the specification limit of 0.7%.

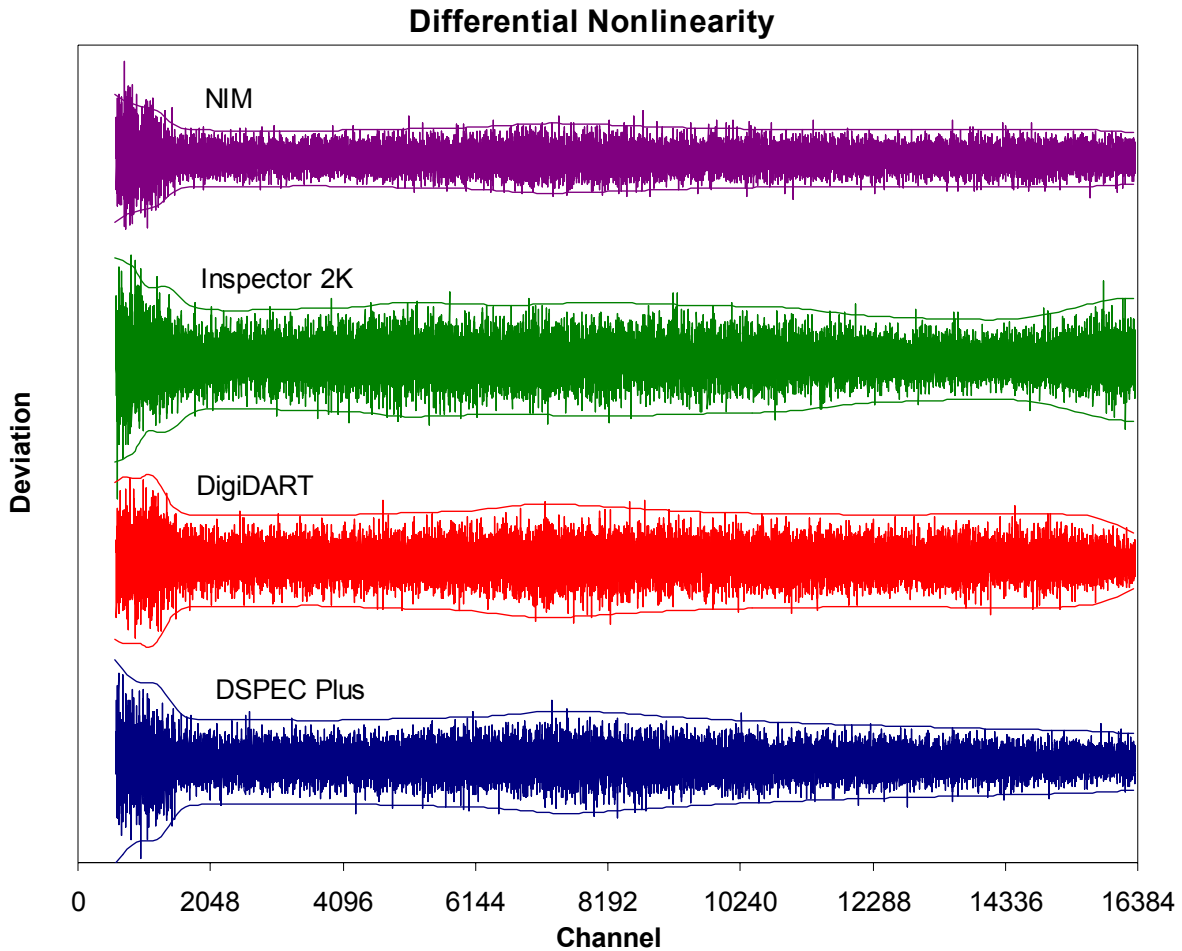


Figure 20: The difference spectra of the four systems.

The number of the channels with the results exceeding 1, 2, 3, and 4 standard deviations were obtained from these spectra. These are compared to the statistical expectation in Table IX. The overall results of the DSPEC Plus and DigiDART systems are consistent with pure statistics. That is, the differential nonlinearity of these two systems are negligible comparing with the statistical variations, which in this case, vary from $\sim 0.03\%$ to $\sim 0.1\%$ (1 sigma) for the low to the high channels.

Table IX. Fraction above the 1, 2, 3, and 4 standard deviations of the three systems comparing with those from pure statistics.

	1 Std. Dev.	2 Std. Dev.	3 Std. Dev.	4 Std. Dev.
Statistics	3.17E-1	4.55E-2	2.70E-3	6.33E-5
DSPEC Plus	3.08E-1	4.25E-2	2.58E-3	0.00E+0
DigiDART	3.08E-1	3.95E-2	1.70E-3	0.00E+0
Inspector 2K	3.23E-1	4.93E-2	3.27E-3	1.26E-4
NIM	3.91E-1	8.32E-2	8.99E-3	6.92E-4

The Inspector 2000 results are almost within statistical limits. Most of the channel range is below and only a small portion is above the DNL of 0.1%. The overall results of the NIM are somewhat worse than the expectation from pure statistics. This means that the

differential nonlinearity of the NIM is not negligible compared with the statistics. However, most, if not all, of the channels have a DNL less than 0.3%, which is still much below the value of 0.7% specified in Table VIII.

Figure 19 shows that the four spectra used to evaluate the DNL of the four systems are completely different. All four systems shared the same input from the NaI detector and their spectra should be very much similar, even though the total counts may not be the same. The NIM system has the largest dead time, so its total count would be somewhat less than that of the other three systems. The Inspector 2000 has the best throughput so it would have the most counts. The total counts of these spectra appear as expected, but the shapes of the spectra do not.

All these systems were originally set such that the Compton edge of the 662 keV peak would be slightly above the midpoint channel (which is 8K out of 16K channels). The coarse gain was then increased by two so that the Compton edge exceeds the 16K channel maximum. The result would be a relatively flat distribution with structure corresponding to the 662-keV backscatter near the midpoint. Enhanced counts in the low channels should also appear because of noise at the large gain of the amplifier.

We see in Figure 19 that only the NIM's spectrum somewhat resembles the described detail, while none of the DSP spectra appear normal. These apparent abnormalities were caused by some defects in their systems.

For the NIM system, one can see that the curve dips slightly near the high-energy end of the spectrum. This bend actually corresponds to the Compton edge of the 662-keV peak and it is normal. It turns out that even though the Compton edge was originally set above the maximum channel, during the long data acquisition, the spectrum was shifted downward slightly which brought the Compton edge below the 16K maximum channel.

The spectrum of the DigiDART also shows the dip near the end like that of the NIM's. However, the magnitude of this dip, which is much greater than that of the NIM, is not caused by the Compton edge. The spectrum of the DSPEC Plus shows a gradual negative slope from the spectrum midpoint toward the end. The cause for both the sharp dip near the end of the DigiDART's spectrum and the gradual dip of the DSPEC Plus' spectrum are believed to be the same. Note that these effects are not only observed for 16K spectra. (Tests performed with 4K and 8K spectra show the same effects).

We took five-minute spectra with the DSPEC Plus and the DigiDART, first with the elevated amplifier gains and then with half that gain. The spectra with the elevated amplifier gains were then compressed by a factor of about 2 to match the spectra with the lower amplifier gains. (The required compression factors are close to but not exactly equal to two). Figure 21 shows the comparison of these spectra.

The gap between the two DSPEC Plus curves increases gradually with increasing channel number. The amplitude of (b) at the high-energy end is only about 75% that of (a) at this energy. This indicates that the DSPEC Plus at full amplifier gain is less efficient at detecting (storing) high-channel signals than low-channel signals.

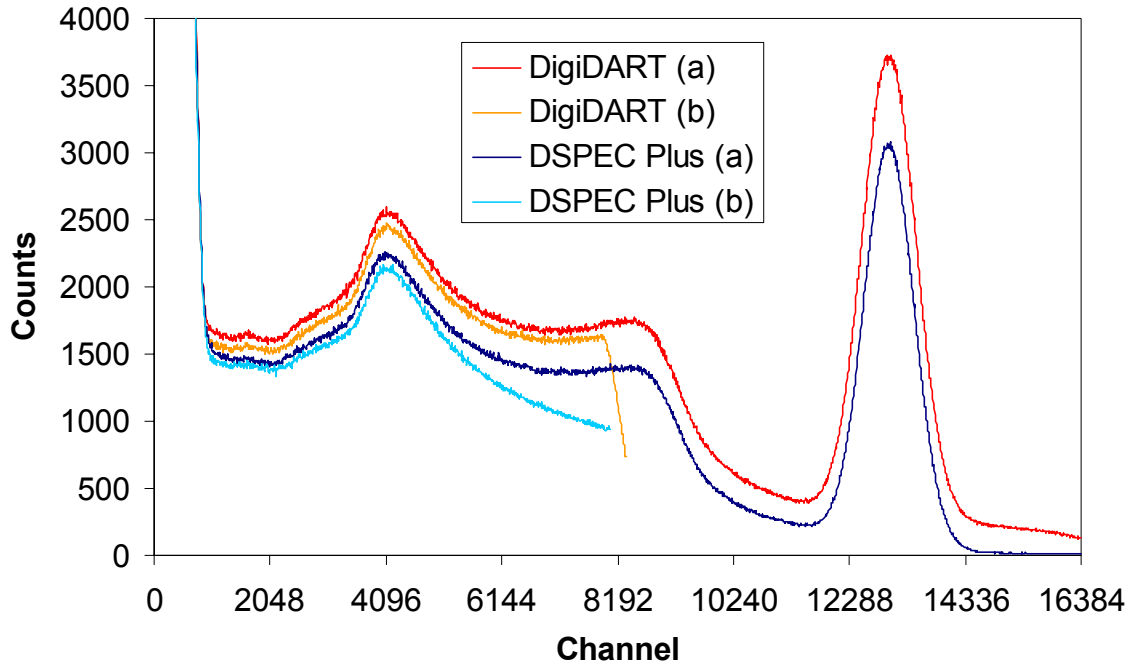


Figure 21: Comparison of the spectra. The order of the spectra from highest to lowest are: DigiDART (a) at half gain, DigiDART (b) at full gain shifted to match (a), DSPEC Plus (a) at half gain, and DSPEC Plus (b) at full gain shifted to match (a). The spectra are shifted slightly in the vertical scale for easy viewing and comparison.

The counts in both DigiDART curves follow one another closely (within $\sim 1\%$) up to $\sim 95\%$ of the maximum channel. Then, approaching the maximum channel, the counts in the full-gain curve (b) dive quickly to only about 50% of those in (a).

The high-gain losses observed in the DSPEC Plus and DigiDART spectra appear different in Figure 21 but have the same cause. Full amplifier gain corresponds to a coarse gain of 20 for the DSPEC Plus and 16 for the DigiDART. The half amplifier gains are 10 and 8, respectively. The problems disappear at coarse gain settings of 10 (for the DSPEC Plus) or 8 (for the DigiDART). Also, this problem affects only the NaI detector but not the HPGe detectors. We postulate that the extra large electronic noise introduced by the amplifier circuitry at coarse gain settings of 20 (16 for the DigiDART) and larger—mentioned in section III.C.1—somehow affects the detection of high-energy pulses especially. The reason that it affects the NaI and not HPGe spectra is probably a combination of both the high-gain electronic noise and the noise from the detector, which is typically larger for NaI than for HPGe. When the amplifier coarse gain is set below 20 (16 for DigiDART) or if the detector is HPGe, the noise combination falls below the threshold, and no abnormality occurs.

Note that in section III.C.1, we mentioned that the count rate indicator shows an increase of about 6% in the input rate with the HPGe detector when the amplifier gain of the DSPEC Plus is switched from $\times 10$ to $\times 20$. The increase in the count rate indicator is much greater—up to 25% for large input rate (100 kHz) and 40% for small input rate (10 kHz)—with the NaI detector when the coarse gain is switched from $\times 10$ to $\times 20$. This also indicates that the incremental noise

of the NaI combined with a coarse gain of 20 exceeds the effect with HPGe and a coarse gain of 20.

The problem for the Inspector 2000 in Figure 19 is similar but not identical to that of an incorrect high-gain setting. This problem was actually caused by the sudden peak shift of the Inspector 2000. The high amplifier gain of the Inspector 2000 was originally set such that the spectrum would be similar to those of the other systems. That is, the backscatter peak was at about channel 8,000 and the 662-keV peak was outside the 16K range (channel 25,000) and not recorded. However, sometime during the acquisition, the peaks were suddenly shifted downward such that the backscatter peak was moved to about channel 5,000 and the 662 peak to about channel 16,300. This explains the spectrum of the Inspector 2000 in Figure 19.

E. Rate-loss correction

All the MCAs suffer some rate loss caused by processing time and pile-up. The rate loss is a function of the input rate, amplifier shaping time, and speed at which the ADC processes the pulses. The total rate-related loss from the combined processing time and pile-up in these MCAs is simply reported as dead time. Although each MCA has a mechanism or technique (called the live-time correction) to account for the dead time, they are not all the same and may not accurately compensate for all the losses, especially at high input rate or large dead time. Table I shows the specified accuracy of the live-time correction circuit or function of each system.

Table X. Specified live-time correction accuracies of the systems.

System	Accuracy	Method
Dspec Plus	<3% for input rate <50kHz and rise time < 12 μ s	Gedcke-Hale [1]
DigiDART	<3% for input rate <50kHz and rise time < 12 μ s	Gedcke-Hale [1]
Inspector 2K	<5% for dead time <50%, 5.6 μ s rise time, 0.8 μ s flattop	N/A
NIM	N/A	Westphal [2]

We have evaluated the accuracy of the live-time correction for each system using the most accurate technique for live-time measurement, the reference-source method.

The reference-source method for determining the live time uses an external source that provides a constant-rate gamma-ray peak to the spectrum. This method is very accurate because all the energy peaks in a spectrum suffer the same fractional loss from the combined effect of electronic processing time and pile-up. Therefore, the ratio of the area of each stored data peak to that of the reference peak is rate independent.

We used the ^{241}Am and ^{57}Co sources with the coaxial detector for this test. The 59.5-keV peak of ^{241}Am was used as the reference peak. It was set at a fixed position relative to the detector such that the input rate was 5 kHz. The ^{57}Co source was then positioned such that the desired total input rate was obtained. Two different shaping times (2 and 6 μ s) were used for each system. The data were obtained with a 2- μ s shaping time at input rates of 5, 10, 20, 30, 45, 60, 80, 100, 125, 150, and 180 kHz. The input rates with a 6- μ s shaping time were 5, 10, 20, 30, 45, 60, and 80 kHz. Each spectrum was acquired for 100 live seconds. The 59.5-keV peak area of each spectrum was obtained and compared to that at 5 kHz. The 59.5-keV peak area of all the

spectra at different input rates should be the same as that at 5 kHz if the live-time correction function of a system is correct. This is not the case even though some systems are doing somewhat better than others.

The NIM system uses the Ortec amplifier and the Canberra ADC. The busy signal output of the amplifier is not quite compatible with the dead-time input of the ADC. Therefore, the reported dead time of this NIM system is not correct. (Note that this affects only the reported dead time but not the real dead time or the throughput.) Obtaining an accurate dead time in the ADC input requires the amplifier and ADC to be from the same manufacturer. We used the Canberra amplifier model 2025 together with the Canberra ADC for the verification test. (This amplifier was shown to be comparable to the Ortec 672 Spectroscopy Amplifier [1] in performance).

Figure 22 shows the accuracy of the live-time correction (the rate of the reference peak relative to that at 5 kHz) at all input rates and both shaping times. All four systems appear to possess some small undercorrection for dead time at small input rates, up to 100 kHz for 2- μ s shaping time and 30 kHz for 6- μ s shaping time. At very large input rates, the systems' live-time corrections break down, as expected.

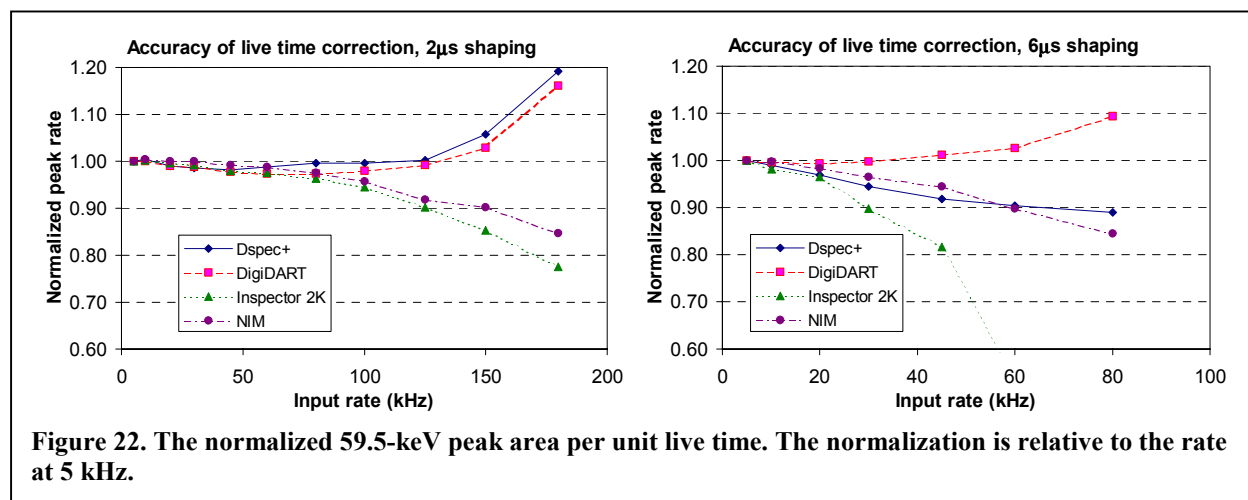


Figure 22. The normalized 59.5-keV peak area per unit live time. The normalization is relative to the rate at 5 kHz.

Figure 23 shows the accuracy of the live-time correction vs % live time. This is perhaps the better way to look at it, because it should be independent of the shaping time. However, the results from the two different shaping times show that the correction does vary with shaping time. Except for the analog NIM system where the accuracy of the live-time correction appears to be similar for both shaping times, the accuracy for the three DSP systems at the two shaping times are different. Overall, the accuracy of the live-time corrections for the NIM system is about the same at both shaping times. The accuracy of the live-time corrections for the DigiDART is better at the 6- μ s shaping time than at 2 μ s (in the tested ranges of input rate). The accuracy of the live-time corrections for the Dspec Plus and Inspector 2K is better at the 2- μ s shaping time. It is unknown why the accuracy of the live-time correction for the Inspector 2K is much worse at the 6- μ s shaping time (compared to that at 2 μ s).

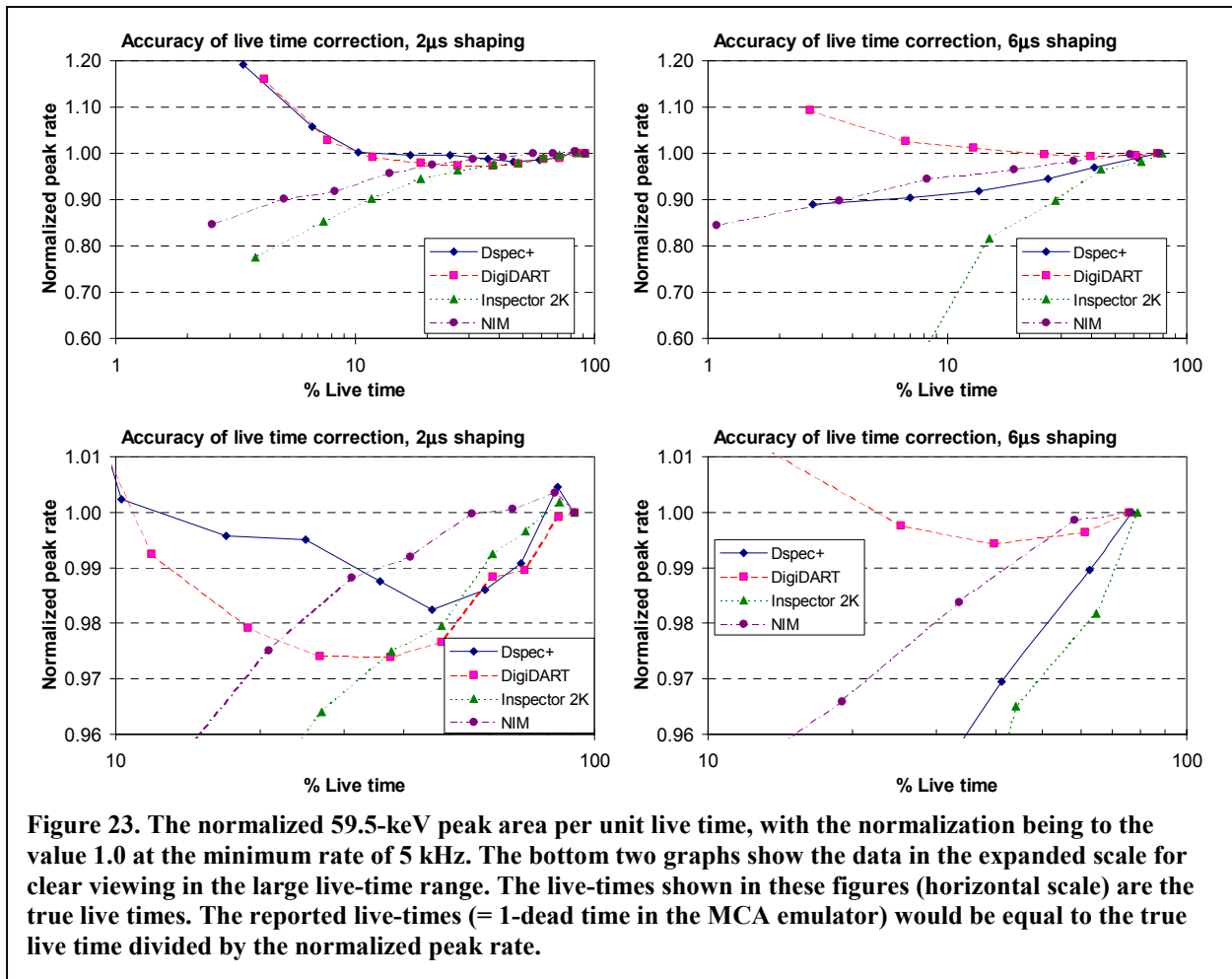


Figure 23. The normalized 59.5-keV peak area per unit live time, with the normalization being to the value 1.0 at the minimum rate of 5 kHz. The bottom two graphs show the data in the expanded scale for clear viewing in the large live-time range. The live-times shown in these figures (horizontal scale) are the true live times. The reported live-times (= 1-dead time in the MCA emulator) would be equal to the true live time divided by the normalized peak rate.

The previous section shows that the dead time should be equal to or less than about 65% for optimal operation of any system. This means that the live time for optimal operation should be about 35% or larger. The correction is accurate to better than 4% for live time in that range, which is approximately consistent with the specifications given in Table I. This may be good enough for some applications but not for some others. We suggest that the reference-source method be used instead of depending on the reported live time or dead time of the systems for applications requiring excellent live-time correction.

F. Problems with the systems

The three DSP systems perform very well compared with the analog NIM system. However, all three DSP systems have some problems that should be investigated and rectified. Some of these problems are small, avoidable, or insignificant. Some are large and serious and could compromise the measurements and analysis. Note that these may not be the only problems associated with these systems but are what we observed in setting up and acquiring data for this evaluation.

We found two problems with the DSPEC Plus. The first one is the large electronic noise associated with the amplifier coarse gain of 20 or larger (described in sections III.C.1 and III.D.2). This noise affects the observed input rate of both the HPGe and NaI detectors and the

pulse detection efficiency of the NaI detectors. The reduced throughput of the HPGe detectors is insignificant but is quite large for the NaI detector. It also somewhat affects the peak position and resolution of the HPGe detectors at very high input rate (greater than 140 kHz). The effect is negligible at low input rates.

The second problem with the DSPEC Plus occurs with a rise time of 3.2 μs and larger. As described in section III.C.1, when the rise time of 3.2 μs or larger is used in combination with an amplifier coarse gain of 10, the resolution broadens and the peaks shift dramatically for input rates greater than 180 kHz. When it is used in combination with a coarse gain of 20, the large changes start at even lower rates, namely 140 kHz. No large peak shift or peak broadening is observed, regardless of coarse gain, up to the tested 300-kHz input rate if a rise time of 3.0 μs or less is used. This problem is not serious because the small rise time (3 μs or less) should always be used—and the large peak shift or broadening would never occur—at very large input rates.

We observed two problems with the DigiDART. The first involves the amplifier at coarse-gain settings of 16 or larger and is like the first problem described for the DSPEC Plus. Because the technologies of the DSPEC Plus and that of the DigiDART are similar, we expect that the DigiDART also has the rise-time problem (second problem described for the DSPEC Plus) when the rise time exceeds a certain value and the input exceeds a certain rate. These rise time and input rate values may not be the same as those documented for the DSPEC Plus (3.2 μs and 140 kHz). We do not have a DigiDART on hand, at the time of this writing, to test this speculation.

The second problem with the DigiDART is that it takes a very long time, up to five minutes, to automatically optimize and PZ the system. The required input rate for the auto-optimization is 5 kHz or less, which is rather low and may possibly not be attained under some measurement circumstances. The system sometimes can and sometimes cannot optimize and PZ at input rates between 5 and 10 kHz, depending on the input rate and how close to optimization the original set up is. Failure to optimize is more likely for a setup that is far from optimal. The optimization would likely fail, even if the original setup were already optimized, at input rates above 10 kHz. That is, if the original setup is near or at the optimum, the result would be worse than the original set up. This problem is minute and should not affect the normal operation of the system, because when the DigiDART is already optimized for a certain detector, there is no need to reoptimize it every time that DigiDART/detector combination is used.

We have documented six problems with the Inspector 2000. The first three summarized below are serious problems.

1. The first problem is the dependence of resolution on amplifier gain. The effect is more profound with the coarse gain than the fine gain. The resolution is better at large coarse and fine gain settings and becomes worse as the coarse or fine gain is reduced. The resolution at a coarse gain of 2.5 is about 3 times worse than that at a coarse gain of 80. The largest degradation of the resolution occurs when the coarse gain is changed from 10 to 5 with the resolution increasing by a factor of about two in this case. The dependence on the fine gain is much smaller, with the resolution at the minimum fine gain setting (0.9) only about 6% worse than that at the maximum fine gain setting (1.9). This dependence of the resolution on the amplifier gain occurs at all gamma-ray energies that we tested, from 60 keV to 1408 keV.

2. The second serious problem is the sudden peak shift described in section III.D.2. This peak shift problem happens with both the HPGe and NaI detector. When it occurs, the peaks shift

proportionally as if a new amplifier gain has been set, despite no change (this has been verified) in the setup. The Inspector 2000 will retain the new apparent amplifier gain for all subsequent measurements if there is no deliberate change in the setup. However, if the amplifier gain setting (either fine or coarse) is adjusted and then readjusted to the original value, then the apparent gain returns to normal.

3. A third serious problem is the inconsistent peak broadening that happens when the rise time is changed from one value to another. When the rise time is changed, depending on the input rate, we expect the resolution to improve or worsen by a well-defined amount. However, sometimes, the change is worse than expected. The resolution after a given change of the rise time may be from several percent up to 100% worse than expected. When it is very much worse than expected, the user may notice something is wrong with the system, but when it is only few percent worse, it may not be possible to notice the problem unless there is a diagnostic to test for it. This problem is temporarily rectified by adjusting the rise time to a different setting and then back to the intended setting. Sometimes several such adjustments are needed before the resolution is normal for the intended setting.

4. The Inspector 2000 exhibits a problem of incomplete data acquisition. Sometimes, when the data acquisition has been almost completed, instead of ending the acquisition and writing the data file to disk (if programmed to do so), it disconnects. The user needs to physically click on the stop button to end the acquisition. This is not a major problem for attended, single-spectrum acquisition because the user can manually stop the acquisition and then save the data to a disk. However, for an unattended, multiple-spectrum acquisition, the disconnection causes a loss of production time because all spectra subsequent to the disconnection are not obtained until the user manually terminates the stalled acquisition to continue the cycle.

5. It is difficult for the computer to communicate with the Inspector 2000 through the serial link. The Inspector-2000/computer communication cannot be established if the Inspector-2000/computer connection is made after it was turned on and booted up. The user must reboot the computer (sometimes several times) with the Inspector 2000 connected and turned on to achieve the communication. This problem could also be specific to the computers used in these tests, which may not communicate well at the suggested rate (57 kbauds) for serial RS-232 connection. We do not observe this problem with the USB connection.

6. The large change in peak position as a function of time was described in section III.C.2. Although these changes are not much larger than that of the NIM system and do not cause the peak resolution to degrade much after long acquisition times, they are many times greater than the specification limit and should be corrected.

The first three problems with the Inspector 2000 are serious and need immediate manufacturer's attention. We sent our two Inspector 2000 units back to the manufacturer to have the first four problems corrected. We are able to confirm the correction of the first and fourth problems. The second and third problems occur intermittently and may appear only after extensive usage and testing, which we have not done. So we cannot draw any conclusions regarding them, as yet.

IV. Conclusion

Four gamma-ray spectroscopy systems were tested for

- Resolution and throughput performance as a function of input count rate and shaping time.
- Stability as a function of both input count rate and long-term acquisition.
- Nonlinearity.
- Rate-loss correction

The resolution and throughput performance of the three DSP systems are much better than those of the analog NIM system, especially with the coaxial detector measuring the high-energy (^{60}Co) spectrum. The DSPEC Plus appears to be the best at low input rate and long shaping time while the Inspector 2000 is the best at high input rate and short shaping time. The DigiDART is slightly worse than the other two DSP systems but is still excellent compared with the NIM.

The stability as a function of input count rate is comparable for all four systems. Because the detectors themselves exhibit large peak shifts as a function of input rate, even larger than those of the MCAs, this comparison of the four systems is inconclusive.

The stability as a function of time (long-term acquisition) of the DSPEC Plus and DigiDART are excellent. The NIM is somewhat worse but still well within the specification limit. The Inspector 2000 appears to have a problem with long-term stability and is the worst system in this test.

The integral nonlinearity of the DSPEC Plus and NIM are excellent and much better than the other two systems. We think that the integral nonlinearity specifications for these four systems are stated too conservatively. (The performances of the DSPEC Plus and NIM systems are 10-times better than their specifications). Although the DigiDART and the Inspector 2000 perform within their specifications, we believe that these can be significantly improved.

The differential nonlinearity of both the DSPEC Plus and the DigiDART is negligible (perhaps one or two orders of magnitude better than the specification). The Inspector 2000 has a noticeable differential nonlinearity but this is still very small (a factor of 10 better than the specification limit). The NIM system appears to possess some differential nonlinearity, but it is also very small (a factor of two to three better than the specification). We think the specifications for the DSP systems are stated too conservatively. They should be specified at 0.1% or 0.2% instead of 1%.

The rate-loss correction performance is similar for all four systems and consistent with the specification. The accuracies of these rate-loss corrections are probably good enough for most applications. For applications requiring excellent live-time correction, we suggest that the reference-source method be used instead of the rate-loss corrections of the systems.

Overall, the DSP systems have been shown to outperform the NIM system, which is the best analog system today. The DSP systems, including the two new portables (DigiDART and Inspector 2000), are highly recommended for use in simple gamma-ray acquisition systems with germanium detectors.

V. References

1. D. T. Vo, "Extended Evaluations of the Commercial Spectrometer Systems for Safeguards Applications," Los Alamos National Laboratory report LA-13604-MS (August 1999).
2. D. T. Vo, P. A. Russo, and T. E. Sampson, "Comparisons of the DSPEC and DSPEC Plus Spectrometer Systems," Los Alamos National Laboratory report LA-13671-MS (November 1999).