An Innovative Method for Dead Time Correction in Nuclear Spectroscopy

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Abstract

All nuclear spectroscopy systems, whether measuring charged particles, x-rays, or gamma rays, exhibit dead time losses during the counting process due to pulse processing in the electronics. Several techniques have been employed in an effort to reduce the effects of dead time losses on a spectroscopy system including live time clocks and loss-free counting modules. Live time extension techniques give accurate results when measuring samples in which the activity remains roughly constant during the measuring process (i.e., the dead time does not change significantly during a single measurement period). The loss-free counting method of correcting for dead time losses, as introduced by Harms and improved by Westphal (US Patent No. 4,476,384) give better results than live time extension techniques when the counting rate changes significantly during the measurement. However, loss-free counting methods are limited by the fact that an estimation of the uncertainty associated with the spectral counts can not be easily determined, because the corrected data no longer obeys Poisson statistics. Therefore, accurate analysis of the spectral data including the uncertainty calculations is difficult to achieve. The ORTEC® DSPEC*PLUS*™ implements an improved zero dead time method that accurately predicts the uncertainty from counting statistics and overcomes the limitations of previous loss-free counting methods. The uncertainty in the dead-time- corrected spectrum is calculated and stored with the spectral data (Patent Pending). The GammaVision-32® analysis algorithm has been improved to propagate this uncertainty through the activity calculation. Two experiments are set up to verify these innovations. The experiments show that the new method gives the same reported activity and associated uncertainties as the well-proven Gedcke-Hale live time clock. It is thus shown that over a wide range of dead times the new ZDT method tracks the true counting rate as if it had zero dead time, and yields an accurate estimation of the statistical uncertainty in the reported counts.

Introduction

The use of spectroscopy equipment for the identification of radioactive materials in a variety of applications in the nuclear industry continues to expand. The applications include analysis of environmental samples, process control or process verification samples, radiochemical samples, nuclear non-proliferation, environmental effluent and release monitoring, and analysis of chemical composition through the use of neutron activation analysis. Types of samples can range from air filters and beakers of soil or water, to flowing gases, nuclear materials, or vials of a particular chemical. A complete energy-spectroscopy system for nuclear radiation, in general, consists of a scintillation or semiconductor detector, electronics including a Multi Channel Analyzer (MCA), computer, and data acquisition and analysis software.

The electronics in the spectroscopy system utilize some fraction of time, usually on the order of 1 to 70 μsec, to process pulses from the detector. While the electronics are processing one pulse, another pulse can not be processed for that period of time. In these cases, the electronics are “dead” to incoming pulses and this period of time is referred to as "dead time." In instances where the incoming pulse count rates are small (less than a few hundred counts per second) and constant, there is only a small probability that the first pulse will not be completely processed before the next pulse enters the detector. However, in some applications the incoming count rates can be high or change rapidly (from very low count rate to high count rate in less than 100 µsec) to the point where the processing of one pulse overlaps with the incident time of the subsequent pulse. In these cases the probability for dead time losses becomes much higher. In any system, whether low or high count rate, the electronics must accurately compensate for the dead time in order to eliminate the systematic error in quantifying the activity of any particular nuclide in a sample[1].

For accurate activity quantification of a radioactive source in a Multichannel Analyzer, the dead time of the system, and the uncertainty in the number of events counted, must be known. One of the most common methods of compensating for dead time in MCA's is through the use of Live Time Clocks. The uncertainty in the number of counts recorded using a Live Time Clock can be calculated and thus propagated as a source of error in the measurement, an essential quantity in any reported activity analysis. One very accurate Live Time Clock is the Gedcke-Hale clock described by Jenkins, Gould, and Gedcke[2]. However, all such live time extension methods are only accurate if the activity of the source being measured is constant during the measurement period. In the case of short-lived isotopes, such as those routinely encountered in Neutron Activation Analysis, and in the case of so-called "hot particles" in effluent monitoring (short burst of radioactive emissions in an otherwise low activity flow), the Live Time Clocks introduce significant systematic errors, and in general will underestimate the true activity over a counting period[3].

To accommodate rapid count rate changes, the use of a differential dead time correction technique was first suggested by Harms[4,5]. Harms showed that the differential ratio between "real time" and "live time" could be used to instantaneously correct for dead time losses. While accurate up to moderate counting rates, this method is not ideal in all cases. This is due in part because the Harms method does not account for leading-edge pulse pileup, which is a significant source of dead time, particularly at very high counting rates. The Harms method was improved by Westphal by adding a manually-adjusted gating pulse to compensate for leading-edge pile-up. The Westphal differential correction method (DCM) is known as *Loss Free Counting*[6].

The major disadvantage of Loss Free Counting is the inability to compute the statistical uncertainty arising from counting random events. While the spectrum itself exhibits a negligible systematic error in representing the number of pulses that should have been counted had there been no dead time, the random fluctuations of the counts in the peaks no longer follow simple Poisson statistics. Therefore, while Loss Free Counting greatly reduces the systematic errors suffered by the LTC method, the corrected spectrum itself cannot be used to derive the random counting uncertainties. This deficiency has limited the use of Loss Free Counting in typical spectroscopy counting systems. Therefore, the invention of a DCM that includes the ability to quantify the uncertainty of the corrected data is of great significance.

The ORTEC Zero Dead Time Method with Statistical Accuracy Measurement

In 1999, the ORTEC DSPEC^{PLUS} was introduced with a new DCM known as Zero Dead Time, or ZDT™. This unique technique does not rely upon Westphal's method to perform the DCM. Instead, ZDT uses the Gedcke-Hale Live Time Clock internal to the DSPEC^{PLUS} to calculate the incremental counts to be added for the next pulse. The completely digital implementation of this technique means the ZDT correction is done without the need for manual adjustments or calibrations for the dead time correction intervals. This automation makes the setup of the ZDT method trivial in that there are no calibrations to perform, optimizations to choose, or hardware devices to adjust. The DSPEC^{PLUS} ZDT acquire mode is completely software controlled.

In addition to the new DCM supplied in the form of ZDT, the ORTEC DSPEC^{PLUS} now includes an innovative method for determining the uncertainty with the corrected spectrum. This new method, for which a patent has been applied, collects two spectra simultaneously for every channel in the histogram memory. The first spectrum is the ZDT-corrected channel data. The second spectrum consists of the variance associated with the corresponding channel in the ZDT-corrected spectrum and is referred to as the "variance spectrum." Both spectra have the same number of channels and can be up to 16,384.

However, collection of the variance spectrum with the ZDT-corrected spectrum provides only part of the solution for the spectroscopy counting system. Analyses, including a propagation of all uncertainties, especially those from the ZDT technique, are necessary for the quantitative analysis of collected spectra. Therefore, in addition to the new ZDT with variance estimation mode, the ORTEC GammaVision-32® software has been upgraded to include a comprehensive analysis of the ZDT spectrum with an accurate propagation of the uncertainty associated with the data. The data presented below provides experimental confirmation that (1) the variance spectrum collected with the ZDT-corrected spectrum is accurate, and (2) the analysis algorithms incorporated into GammaVision accurately propagate this variance into the total uncertainty of the measurement.

Experimental Setups

Two different experimental setups were used to verify the new techniques for the ZDT correction. The first experiment demonstrates that the variance spectrum is accurate as predicted. The second experiment exercises the new analysis capabilities in GammaVision to demonstrate the statistically correct propagation of errors in the uncertainty calculation. The case of constant counting rate was studied because it can be controlled for precise repeatability. This is essential for testing actual sample variance against predicted sample variance.

Variance Spectrum Validation

To validate the use of the variance estimation in the ZDT analysis spectrum, 1000 ZDT-corrected spectra with the 1000 associated variance spectra were collected at each of several fixed dead time values. Next, the variance for each set of the 1000 ZDT spectra was calculated and compared to the variance predicted by the associated 1000 variance spectra. If the values of the variance agree within statistical limits, then it can be said that the variance estimation algorithm incorporated into the DSPEC^{PLUS} is accurate.

To collect the spectra, a fixed dead time of approximately 16% was established with a Co-60 source. An Y-88 source was then placed in a fixed position to give a constant count rate. With these two sources in position, 1000 spectra were collected and saved to disk. The Co-60 source was then moved so that the fixed dead time was approximately 27% while the Y-88 remained fixed. Another 1000 spectra were collected and saved. This was repeated for fixed dead times of approximately 50%, 70%, and 90%. Results were compiled and compared for the 1.8MeV peak of Y-88, and the 1.33 and 1.17 MeV peaks of Co-60.

Analysis Algorithm Validation

To test the analysis algorithm, two separate acquisitions were made from a single source at fixed locations from a given detector. The first acquisition used the normal Gedcke-Hale Live Time Clock method for a fixed live time of 600 seconds. The second acquisition used the innovative ZDT with variance estimation algorithm for a fixed real time of 600 seconds. The source, a mixed gamma source with calibration certificate traceable to NIST, gives a known dead time at a fixed position from the detector of approximately 20%. The real time in the LTC-accumulated spectra was approximately 755 seconds. Because the source is not decaying rapidly during the count time (shortest half-life in the source is on the order of 43 days compared to a 1 hour measurement time) and the dead time is low, the Live Time Clock in the system is accurate. Thus, the analysis of the Live Time Clock corrected spectrum yields a result for the activity with an accurately predictable counting uncertainty. These results are then compared to the analysis of the ZDT-corrected spectrum.

Results

Variance Spectrum Results

Tables 1 and 2 list the results for all data collected for the validation of the spectral algorithm for calculating the uncertainty in the gross and net peak areas respectively. The column listed as "Computed Variance in Counts" is calculated from the distribution of the actual counts in the listed peak areas of the ZDT-corrected data spectrum. The variance is given by the equation:

$$Variance = \frac{n\sum x^2 - \left(\sum x\right)^2}{n(n-1)} \qquad \text{(Eq. 1)}$$

Where x is either the gross area or net peak area counts in a given region of interest of the ZDT-corrected spectrum and n is the total number of spectra collected (n = 1000).

The variance in the column headed as "Average Variance from the Uncertainty Spectrum" is the statistical average of the calculated variance in each of the variance spectra for the given regions of interest (1173 keV, 1332 keV, and 1836 keV) from the same 1000 spectra. This average is given by:

$$Average\,Variance = \frac{\sum_{i=1}^{n} x_i}{n} \qquad \text{(Eq. 2)}$$

Where x_i is the variance calculated for each region of interest in the variance spectrum for the i^{th} spectra and n is the total number of spectra collected.

The standard deviation on this average is then calculated and plotted in Figures 1-6 at each of the dead time values. In Figures 1-6, the average variance in the uncertainty spectra are plotted in the clear bars while the variance from the corrected spectra are plotted in the shaded bars.

Analysis of ZDT Spectrum Results

Table 3 shows the results of the mixed gamma analysis using the LTC- and the ZDT-corrected spectra including the activities and the uncertainties. The "Average Activity" columns are the average values in Bequerels of the GammaVision-calculated activity for the listed nuclides from the twenty LTC and ZDT-corrected spectra. The "Average Uncertainty" columns are the average of the 1σ total uncertainties as calculated by GammaVision for each of the twenty spectra for LTC and ZDT-corrected counts. The "Standard Deviation in Activity" column gives the 1σ standard deviation in percent of the average activity values. This value was calculated to compare the results of the ZDT and LTC calculated analysis results with error bars. The last two columns calculate the difference in the average activities and the average uncertainties, respectively, for each nuclide.

Figure 7 compares the activity of each nuclide as calculated from LTC (clear bars) spectra and the ZDT (crosshatched bars). The standard deviations of each of these average values are also shown in the form of error bars.

Discussion

Tables 1 and 2 and Figures 1 through 6 clearly show that the variance predicted by the variance spectrum compares with the variance from normal statistical methods. This is true over the range from 10% to 90% as demonstrated here. The algorithm shows no bias toward either over- or under-estimating the errors as shown by the distribution of positive and negative differences in the variances at all three energies of interest.

Table 3 and Figure 7 clearly show that the analysis algorithm incorporated into the ORTEC GammaVision software yields results that are comparable to those collected and analyzed using the traditional Live Time Clock method. The activity and uncertainty calculated by the ZDT-corrected spectra are well within the 1σ standard deviation of the LTC-corrected spectra. The calculated differences in the average activities and average uncertainties do not exceed 2.6% or 4.4% respectively for any nuclide. This is also within the statistical accuracy of the measurement process. Also of note is the lack of any energy dependencies on either the calculation of the areas of the peaks or the propagated uncertainty. This is shown by the analysis of nuclides that span the energy range from 59.5 to 1836 keV.

By combining the results of the two experiments run above, it is clear that (a) the ZDT variance spectrum represents the true uncertainty in the ZDT-corrected spectrum, and (b) the analysis algorithm used to incorporate the ZDT variance spectrum yields the same result as the Live Time Clock method in the limited case where the dead time is not changing rapidly over the measurement time. By incorporation of these innovative techniques, the ORTEC DSPEC^{PLUS} and GammaVision-32 software have the combined effect of giving to the spectroscopy counting laboratory one complete solution for collecting, correcting, and analyzing any sample with no dead time losses yielding quantitative results including an accurate uncertainty estimation.

The testing performed demonstrates that ZDT gives the correct activity and uncertainty over a wide range of dead times. Since ZDT corrects the counts and not the clock, it is clear that sources with changing count rates will be correctly quantified and that the uncertainty of the resulting counts is known. Further experimentation is being conducted to determine the limits associated with very rapidly changing count rates in activation setups and for “hot particles” of activity in real time monitoring applications. Results of these tests will be published when available.

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Table 1. Summary of Gross Peak Area Counts with Predicted versus Calculated Variance.

	16% Dead Time			27% Dead Time			50% Dead Time			70% Dead Time			90% Dead Time		
	1.84 MeV	1.17 MeV	1.33 MeV	1.84 MeV	1.17 MeV	1.33 MeV	1.84 MeV	1.17 MeV	1.33 MeV	1.84 MeV	1.17 MeV	1.33 MeV	1.84 MeV	1.17 MeV	1.33 MeV
Average Gross Counts	20,806	5,026	4,834	20,790	37,967	32,383	21,851	129,480	108,991	23,619	238,933	200,447	30,858	479,080	399,246
Average Variance from Uncertainty Spectrum	27,710	6,693	6,434	32,435	59,251	50,530	49,420	292,821	246,501	87,600	886,142	743,414	317,811	4,934,447	4,112,098
Computed Variance in Gross Counts	28,439	6,063	6,759	30,652	63,512	52,997	50,267	286,939	258,263	81,297	959,605	832,321	312,984	6,345,601	5,531,640
Δ in Variance	**-3%**	**10%**	**-5%**	**6%**	**-7%**	**-5%**	**-2%**	**2%**	**-5%**	**8%**	**-8%**	**-11%**	**2%**	**-22%**	**-26%**

Table 2. Summary of Net Peak Area with Predicted versus Calculated Variance.

	16% Dead Time			27% Dead Time			50% Dead Time			70% Dead Time			90% Dead Time		
	1.84 MeV	1.17 MeV	1.33 MeV	1.84 MeV	1.17 MeV	1.33 MeV	1.84 MeV	1.17 MeV	1.33 MeV	1.84 MeV	1.17 MeV	1.33 MeV	1.84 MeV	1.17 MeV	1.33 MeV
Average Net Counts	20,541	3,206	2,829	20,437	34,018	29,979	20,833	119,051	104,964	20,989	219,616	193,437	22,442	436,730	382,018
Average Variance from Uncertainty Spectrum	33,183	43,954	47,209	40,882	153,631	108,031	84,777	654,126	386,131	237,389	1,984,583	1,142,024	1,646,162	11,619,368	6,833,572
Computed Variance from Net Counts	34,934	47,105	48,288	39,409	164,819	104,126	89,894	682,895	396,247	224,399	2,039,894	1,195,607	1,676,259	12,131,994	7,929,035
Δ in Variance	**-5%**	**-7%**	**-2%**	**4%**	**-7%**	**4%**	**-6%**	**-4%**	**-3%**	**6%**	**-3%**	**-4%**	**-2%**	**-4%**	**-14%**

Table 3. Analysis Results for Live Time and Zero Dead Time Corrected Spectra.

	LTC-Corrected			ZDT-Corrected			Summary	
	Average Act	Average Uncert	Std Dev Act	Average Act	Average Uncert	Std Dev Act	Δ Activity	Δ Uncert.
Am-241	12681	1.51%	7.0%	12761	1.49%	2.8%	0.6%	-1.8%
Cd-109	60338	1.59%	2.8%	58887	1.58%	3.3%	-2.4%	-0.6%
Co-57	684	1.60%	3.3%	673	1.53%	2.8%	-1.6%	-4.4%
Co-60	6857	0.26%	2.8%	6680	0.25%	3.9%	-2.6%	-4.0%
Cs-137	4555	0.43%	4.2%	4519	0.44%	2.9%	-0.8%	0.5%

Figure 7. Calculated Uncertainty for LTC and ZDT Spectra.

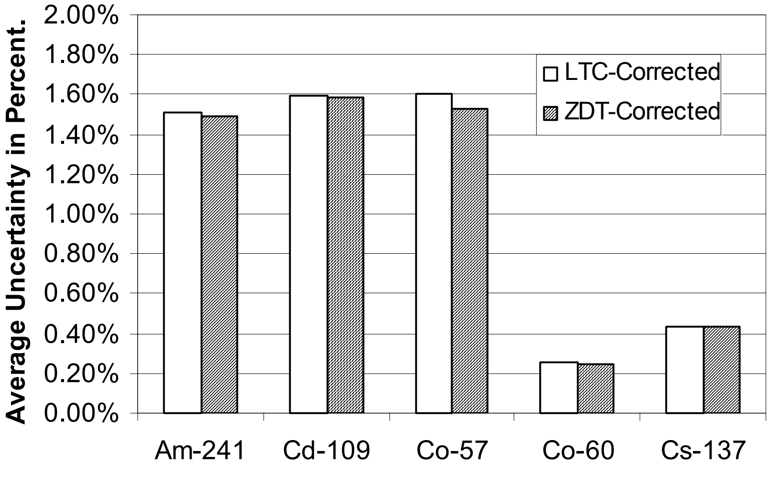


Figure 1. Variance in 1836 keV Gross Peak Area.

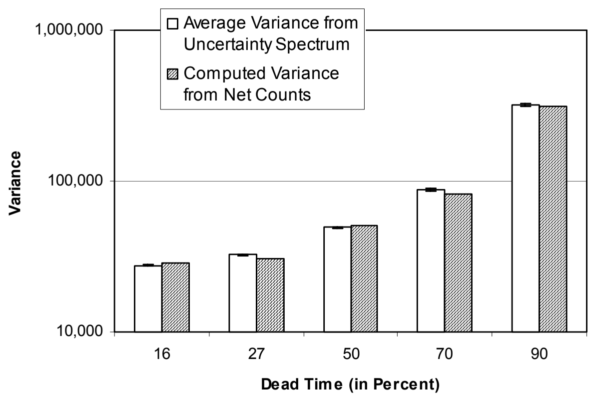


Figure 2. Variance in 1173 keV Gross Peak Area.

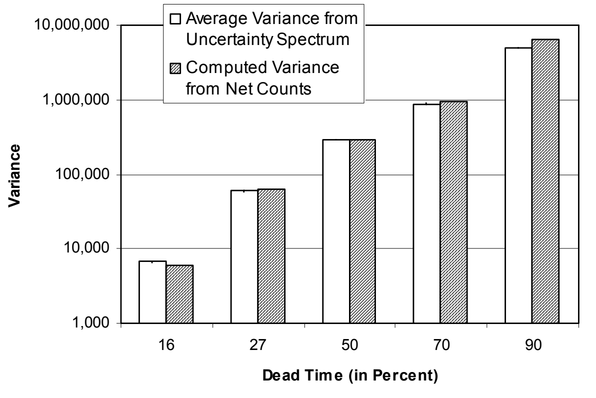


Figure 3. Variance in 1332 keV Gross Peak Area.

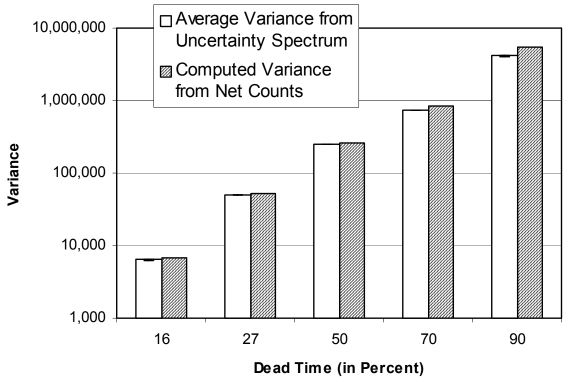


Figure 4. Variance in 1836 keV Net Peak Area.

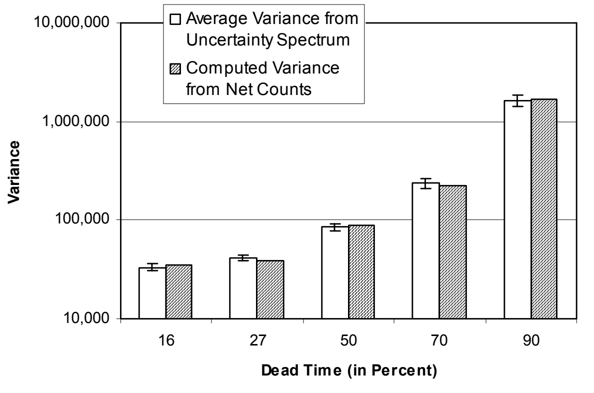


Figure 5. Variance in 1173 Net Peak Area.

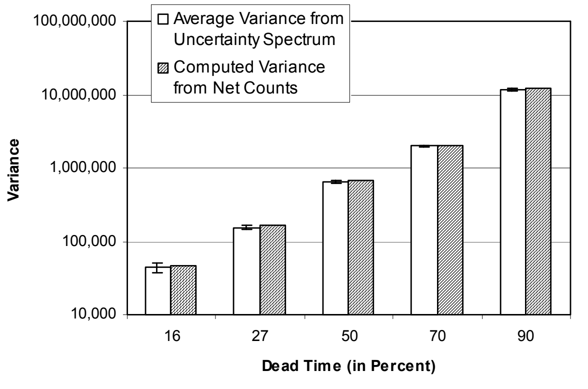
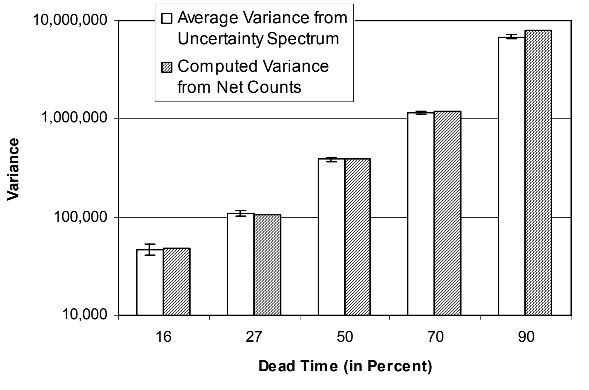


Figure 6. Variance in 1332 keV Net Peak Area.



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