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Application Note AN63

Simply Managing Dead Time Errors in Gamma-Ray Spectrometry

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Synopsis

This application note provides simple processes for overcoming the systematic and random errors caused by dead time in a gamma-ray spectrometer. The applicability of the livetime clock for sources generating essentially constant counting rate, and the Zero Dead Time (ZDT) scheme for sources with changing counting rates are explained. The statistical error to be reported in the measured counting rate is defined in both circumstances. The explanations are related to ORTEC gamma-ray spectrometers. But, with minor adjustments, they can be adapted to energy spectrometers for X rays, alpha particles and beta particles, or spectrometers from other manufacturers.

The Systematic Error Caused by Dead Time

In a gamma-ray spectrometer there is a finite processing time required to measure and record each detected gamma ray. Depending on the spectrometer and its intended use, the processing time is typically in the range of microseconds to tens of microseconds. During this processing time, the spectrometer is not able to respond to another gamma ray. Thus the processing time is normally regarded as a dead time. Because gamma-ray photons arrive at the detector with a random distribution in time, some photons will arrive during this dead time and will not be measured or counted. This constitutes a dead time loss. In other words, the number of gamma rays reported in the measured energy spectrum will be less than the number of gamma rays that impinged on the detector during the measurement period.

For a spectrum accumulation that lasts for a real time of T_R seconds, the relationship between the real time, the total dead time, T_D, and the total live time, T_L, is

$$T_L = T_R - T_D \qquad (1)$$

The real time, T_R, is the elapsed time over which the spectrum is accumulated, as measured with a standard stop-watch, or the clock on the wall. The total dead time, T_D, is the sum of all the individual dead time intervals during that accumulation. The residual, after subtracting T_D from T_R, is the total live time, T_L, i.e., the total time during which the spectrometer was able to respond to another gamma ray.

Spectrometers usually report the percent dead time so that the operator is aware of the severity of the dead time losses. The percent dead time, %DT, can be derived from equation (1) in the form

$$\%DT = \frac{T_D}{T_R} \text{ x } 100\% = (1 - \frac{T_L}{T_R}) \text{ x } 100\% \qquad (2)$$

Operating conditions that result in greater than 63% dead time should be avoided, where possible, because the systematic errors in the dead time correction escalate above that point. Moreover, most gamma-ray spectrometers incorporate paralyzable dead time (a.k.a., extending dead time) as the dominant component of their dead time. With paralyzable dead time, the maximum recorded counting rate is achieved at 63% dead time. Beyond 63% dead time, increasing the counting rate at the detector actually decreases the counting rate recorded in the analyzed spectrum[1,2].

Correcting for Dead Time Losses

The schemes for correcting for dead time losses can be separated into two main categories: a) the counting rate of the source of gamma rays is essentially constant over the time taken to accumulate the spectrum, and b) the counting rate varies significantly during the accumulation of the energy spectrum.

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The Live Time Clock for Constant Counting Rates

Probably, the most common situation is measuring the energy spectrum and activities of radioisotopes whose half lives are very long compared to the time required to accumulate the energy spectrum with sufficient statistical precision. In this case, the counting rate and the percent dead time are essentially constant during the measurement of the spectrum. A convenient and effective tool for correcting the dead time losses when the counting rates are steady is the livetime clock[1,2]. This is an electronic clock that counts the ticks of elapsed time only when the spectrometer is live and able to respond to another gamma-ray event. This is like measuring the constant rate at which water is flowing out of a pipe by filling a 1-liter bucket and then dumping the bucket on the ground. Dumping the bucket constitutes dead time. If you measure only the time it takes to fill the bucket, you will be able to calculate the flow rate in liters per second by dividing by the filling time. You don't count the time while you are emptying the bucket, because that is dead time. To improve the precision of the answer, this measurement can be repeated over a large number of 1-liter fillings, with the stop watch accumulating time during the filling phase, but stopped during the dumping time. At the end of the process, the correct flow rate is obtained by dividing the number of liters filled by the live time recorded on the stop watch.

Because the gamma rays are generated by the radioactive source with a random distribution in time, the number of gamma rays counted in a fixed time interval is a stochastic variable. If the energy spectrum is accumulated for a preset live time, T_L, then Poisson Statistics applies[1]. Therefore, the standard deviation in the recorded counts, N_L, in a region of interest set across a specific peak in the spectrum will be[1]

$$\sigma_{NL} = \sqrt{N_L} \qquad (3)$$

What is of interest to the gamma-ray spectrometrist is the activity of the radioisotope, and that is proportional to the counting rate in the peak. By dividing the recorded counts by the live time, one calculates the true counting rate at the detector, free of dead time losses.

$$R_i = \frac{N_L}{T_L} \qquad (4)$$

The subscript on the counting rate, R_i, denotes that this is the true **i**nput rate of gamma rays at the detector for the selected peak in the energy spectrum.

In this case, the live time is considered a deterministically measured variable, and the standard formula for propagation of statistical errors[3] yields

$$\sigma_{Ri} = \frac{\sqrt{N_L}}{T_L} \qquad (5)$$

where σ_{Ri} is the standard deviation in the counting rate, R_i.

Because the dead time intervals are generated by the randomly arriving gamma rays, there is a random variation in the ratio of T_R/T_L. Consequently, the standard deviation in the number of counts recorded in a preset **real** time is not simply the square root of the number of counts. Furthermore, the standard deviation in the counts recorded for a preset real time is difficult to calculate[1,6,7]. But fortunately, equations (4) and (5) are applicable, no matter how the acquisition of the spectrum is stopped. ***In other words, always divide the recorded counts by the live time. This yields the true input counting rate, and provides a simple way to calculate the standard deviation in that counting rate.***

From equations (4) and (5) one can derive the percent standard deviation in the measured input rate, which is

$$\%\sigma_{Ri} = \frac{\sigma_{Ri}}{R_i} \text{ x } 100\% = \frac{100\%}{\sqrt{N_L}} \qquad (6)$$

Table 1 shows how the precision from counting statistics depends on the number of counts recorded in a preset live time. More than 10,000 counts are required to achieve a precision less than 1%.

To see how this degrades when background must be subtracted from the peak in the energy spectrum, see reference 4. To simplify the discussion, this application note will ignore the background subtraction issue.

Table 1. Percent Precision from Counting Statistics versus Live Time Counts.

N_L	$\%\sigma_{Ri}$
1	100
100	10
10,000	1
1,000,000	0.1

Precision Limitations in the Livetime Clock

Clock Tick Period: The electronic clock employed to measure the elapsed real time and live time is usually based on a crystal-controlled oscillator that generates a period t_c between clock ticks. The clock ticks are counted and multiplied by the appropriate constant to express the measured time in seconds. When a preset time limit is set, the electronic clock ticks are counted to determine when that limit is reached, thus stopping the acquisition. To make an accurate measurement of the dead time on each gamma-ray pulse, the period t_c must be short compared to the pulse width caused by the gamma-ray event. Typically t_c is designed to be in the range of 100 to 500 ns. When operating for a preset live time or a preset real time, there is an uncertainty of ±1/2 clock period in accounting for the actual elapsed time. In virtually all cases, the preset time interval will be long enough (e.g., >20 ms) so that this quantization error is negligible (<0.0025%).

Truncation of the Reported Live Time: A second error can arise from the quantization limit set by the least significant digit in the live time as reported by the hardware or software. Typically, this precision limit is chosen by design in the range of 10 ms to 1 s. If the spectrometer is operated for a preset real time, this quantization limit controls the precision of the displayed live time. If the live time is large compared to the least significant digit, this quantization limit contributes a negligible error to the measurement of the counting rate. But, the precision of the reported live time can introduce a significant uncertainty in the calculated counting rate when the elapsed live time for the measurement approaches the magnitude of the least significant digit. In that case, the live time precision becomes a limitation on the measurement precision. This limitation on the live time precision only applies when operating for a preset real time, or when the acquisition is stopped manually. Counting for a preset live time eliminates this error.

The Systematic Dead Time Error: The third source of error becomes important when the percent dead time is very large. Pulse height discriminators are normally set just above the noise level to measure the duration of the gamma-ray pulses, in order to assess the dead time caused by each pulse. Unfortunately, these pulses have leading and falling edges that are not very abrupt. The initial rise out of the noise is sluggish, and the falling edge is slow to disappear into the noise. This makes it difficult to make an accurate measurement of the dead time caused by each pulse. Low-energy pulses that exhibit a very low signal-to-noise ratio also present a challenge for measuring their dead time contribution.

To see why the accuracy of dead time measurement is important at high percent dead times, but insignificant at low percent dead times, consider the following simple example. Presume that the measurement of the dead time interval has a systematically high 0.01 relative error. When the dead time is 1%, the live time is 99%. Consequently, the dead time will be overestimated by 0.01 x 1% = 0.01%, which is a relative error of 0.01%/99% in the live time. That is approximately a 0.01% live time error. Such a small error will virtually always be negligible compared to the larger statistical error resulting from counting random gamma-ray events.

At the other end of the range, consider a 90% dead time. The corresponding live time is 10%. The 0.01 relative error in the dead time measurement yields a 0.01 x 90% = 0.9% error in the total dead time. This is a relative error in the live time given by 0.9%/10% = 0.09. That is a 9% error in the measurement of the live time. Because the dead time was systematically overestimated, the live time will be systematically underestimated, and the counting rate will be overestimated by 9%.

Often, manufacturers will pick a high percent dead time and specify an upper limit for the systematic live time error at that percent dead time. Usually, operating at a lower percent dead time will result in a noticeably lower live time error.

ZDT for Varying Counting Rates

Applications with varying counting rates are sometimes encountered in gamma-ray spectrometry. One example is the monitoring of coolant pipes for contaminants in a nuclear power reactor. A brief surge in contamination will cause the counting rate to rise and fall abruptly. Another example is the analysis of samples activated by neutrons in a nuclear reactor. The sample almost always exhibits initially high counting rates from short-lived isotopes, followed by lower counting rates from radioisotopes having much longer half-lives. If the counting rate changes significantly during the time taken to acquire the energy spectrum, the simple livetime clock will yield the wrong counting rate. In the case of neutron activation analysis, the initially high counting rates cause a high percent dead time, and the spectrometer tries to compensate by extending the counting time. But, the counting time is extended while the counting rate is low, and this distorts the spectrum. The counts for the short-lived isotopes will be systematically depressed and the long half-life content will be artificially increased.

The ORTEC Zero Dead Time algorithm[5] overcomes this problem with rapidly changing counting rates by making the dead time corrections over time intervals that are short enough to experience insignificant changes in counting rate.

The Constant Counting Rate Approximation: To achieve a simple understanding of the method, consider measuring a source that has a constant counting rate. At the end of the preset live time, T_L, the region of interest on a peak in the spectrum contains a number of counts, N_u, which we will call the uncorrected counts. From the definition of live time and real time, the counting rate at the detector in the region of interest is

$$R_i = \frac{N_u}{T_L} = \frac{N_c}{T_R} \qquad (7)$$

N_c, the "corrected" counts, represents the number of events that should have been recorded if there had been no dead time. From equation (7) N_c can be calculated as

$$N_c = \left[\frac{T_R}{T_L}\right] N_u = r\, N_u \qquad (8)$$

The real time to live time ratio in equation (8) is represented more succinctly by

$$r = \frac{T_R}{T_L} \qquad (9)$$

The statistical variance in N_c can be calculated from the standard formula for the propagation of errors[3] as

$$\sigma^2_{Nc} = \sigma^2_{Nu}\left(\frac{\partial N_c}{\partial N_u}\right)^2 + \sigma^2_r\left(\frac{\partial N_c}{\partial r}\right)^2 + 2\sigma^2_{rNu}\left(\frac{\partial N_c}{\partial r}\right)\left(\frac{\partial N_c}{\partial N_u}\right) \qquad (10)$$

Where the terms in parentheses are partial derivatives of equation (8) with respect to the variables on the right side of equation (8), $(\sigma_{rNu})^2$ is the covariance between r and N_u, and the statistical variance in r is $(\sigma_r)^2$. Because the counts were acquired for a preset live time, the variance in N_u, is given by

$$\sigma^2_{Nu} = N_u \qquad (11)$$

For the case where the counting rate in the region of interest is a small fraction, f, of the total counting rate in the spectrum, Pommé[6, 7] has shown that the second and third terms in equation (10) are negligible and can be deleted. (See Appendix A for an explanation.) Therefore, equation (10) simplifies to

$$\sigma^2_{Nc} = r^2\, N_u \qquad (12)$$

Thus, the standard deviation in the corrected counts is

$$\sigma_{Nc} = r\sqrt{N_u} \qquad (13)$$

When the counts in the integrated region of interest are not a small fraction of the total counts in the spectrum, equations (12) and (13) underestimate the statistical error in N_c. Practical measurements[6] have demonstrated that the standard deviation in the total spectrum counts can be as much as a factor of 1.45 higher than indicated by equation (13) when the percent dead time is 70%. However, the gamma-ray spectrometrist is normally interested in the activities of the radioisotopes as derived from the counting rates in the peaks. The counting rate in a peak for a specific isotope virtually always represents a small fraction of the counting rate in the entire spectrum. Therefore, equation (13) is applicable in this normal case.

With this scheme for obtaining the corrected counts, the true input counting rate at the detector for the peak in the region of interest is given by

$$R_i = \frac{N_c}{T_R} = \frac{rN_u}{T_R} \qquad (14)$$

Note that the corrected counts are divided by the real time to calculate the true input counting rate. The standard deviation in this calculated counting rate is

$$\sigma_{Ric} = \frac{\sqrt{\sigma^2_{Nc}}}{T_R} = \frac{\sqrt{r^2 N_u}}{T_R} \qquad (15)$$

Adapting to Changing Counting Rates: If the counting rates are changing significantly during the spectrum acquisition, equations (7) through (9) and (11) to (15) do not yield the right answer. This happens because the real time to live time ratio, r, is changing during the acquisition. The average value of r is available at the end of the acquisition. But, the average value of r^2 required in equation (12) is not equal to the square of the average value of r.

The ZDT electronics solves this problem by breaking up the acquisition into differential time intervals that are so short that the counting rate does not change appreciably during the differential interval. The duration of the differential time interval is typically chosen by the design engineer to be in the range of 0.1 to 1.5 ms. This subdivision is based on real time to avoid lengthening at high percent dead times.

During each differential time interval the current ratio of real time to live time is measured. When an event is accepted by the analyzer, instead of adding one count to the appropriate energy channel, the counts in that memory location are incremented by r counts, where r is the instantaneous value of the real time to live time ratio. This generates the corrected counts from the uncorrected counts instantaneously on each accepted event. Consequently, the correction is able to follow the changing values of r caused by the changing counting rates. At the end of the acquisition, the “Corrected” spectrum contains the counts corrected in real time for the dead time loss. This spectrum represents the spectrum of gamma-rays received by the detector over the real time of the acquisition, undistorted by dead time losses.

The statistical variance in the corrected counts is similarly obtained by adapting equation (12) to the differential time intervals. The memory of the analyzer is divided into two equal segments. The first segment contains the energy spectrum corrected for dead time losses. This is the “ZDT Corrected Spectrum”. The second spectrum is typically called the “ZDT Error Spectrum”. It uses the same energy scale as the corrected spectrum. But, the numbers in each energy channel of the error spectrum represent the variance in the counts in the corresponding channel in the corrected spectrum.

The error spectrum is also generated on an event-by-event basis. When a gamma-ray event is accepted by the analyzer, the instantaneous value of r^2 is added to the content of the appropriate energy channel in the error spectrum. As can be deduced from equation (12), the variance for a single count is r^2, because $N_u = 1$. The well known result for combining independent random errors states that the variance of the sum of numbers is simply the sum of the individual variances[3]. Consequently, summing the individual values of r^2 in the error spectrum correctly reports the variance in the sum of the r values tallied in the corrected energy spectrum in the same energy channel.

In practice, one sets a region of interest across a peak in the ZDT corrected spectrum and sums the counts in that region of interest to report the corrected counts in the peak, N_c. To predict the standard deviation in the peak counts, one sums the variances over the same channels in the ZDT error spectrum and takes the square root of that sum. In other words, the variance in N_c is

$$\sigma_{Nc}^2 = E \qquad (16)$$

Where E is the sum of the numbers in the ZDT error spectrum over the same channels used to sum the counts in the ZDT corrected spectrum. Obviously, the estimated standard deviation in the N_c counts is simply

$$\sigma_{Nc} = \sqrt{E} \qquad (17)$$

Note, for completeness, that the counting rate at the detector is calculated by dividing the corrected counts by the elapsed real time, i.e.,

$$R_i = \frac{N_c}{T_R} \qquad (18)$$

and the standard deviation in the calculated R_i is estimated from

$$\sigma_{Ri} = \frac{\sqrt{E}}{T_R} \qquad (19)$$

Thus the ZDT algorithms provide a means of correcting for dead time losses differentially in real time, with the ability to predict the standard deviation in the corrected counts, even when the counting rates and percent dead time change drastically during the acquisition period.

Pragmatic verification of the effectiveness and accuracy of the ZDT method is evidenced by the extensive testing reported in references 6, and 8 through 13.

Summary for Implementation

The important points regarding the various operating conditions can be summarized as follows.

1) **For counting rates that are essentially constant** during the time required to acquire an energy spectrum:

a) When acquiring for a preset live time, the estimated standard deviation in the recorded counts is simply the square root of the number of counts. (This simple statement is not true when acquiring for a preset real time.)

b) To find the true counting rate at the detector (corrected for dead time losses), divide the recorded counts by the elapsed live time. This procedure is applicable no matter how the acquisition is stopped (manually, by preset counts, by preset real time, or by present live time).

c) No matter how the acquisition is stopped, the estimated standard deviation in the calculated counting rate from 1b) above is the square root of the number of counts divided by the live time.

2) **For rapidly changing counting rates,** where the percent dead time changes appreciably during the acquisition of the energy spectrum, use the ORTEC ZDT mode.

a) The counts corrected for dead time losses are found by integrating the counts in a peak from the ZDT Corrected Spectrum.

b) The variance in the counts from the peak is obtained by summing the numbers in the ZDT Error Spectrum over the same channels used to sum the counts in the peak. The estimated standard deviation is simply the square root of the variance summed from the ZDT Error Spectrum.

c) The counting rate at the detector (corrected for dead time losses) is the corrected counts from step 2a) divided by the elapsed real time.

d) The estimated standard deviation in the counting rate at the detector is the standard deviation from step 2b) divided by the elapsed real time.

3) **To avoid systematic errors** and digital truncation errors in the livetime correction

a) Employ total acquisition times that are large compared to the reported least significant digit from the livetime clock.

b) Avoid percent dead times in excess of 63% wherever possible.

Appendix A: Justification for Ignoring the Variance in r

In general, the number of gamma-rays arriving at the detector in a prescribed real time has a statistical variation. Because each gamma-ray that produces an electrical pulse in the detector will increase the dead time, there is a positive correlation between the number of arriving gamma-rays and the dead time. With respect to the live time, the correlation is negative, because increased dead time corresponds to decreased live time. Thus, in general, one would expect a significant variance for r and a significant covariance between N_u and r in equation (10). This expectation is supported from the reported practical experiments that measure the variance in the corrected counts in the total energy spectrum using the ZDT algorithm[6].

For the case where the corrected counts are summed from an individual peak in the spectrum, the counts in the peak represent a small fraction, f, of the total counts in the spectrum. If one separates the dead time caused by the f fraction of events from the remaining (1–f) fraction of events in the spectrum, it becomes apparent that the percent dead time caused by the f fraction is very small compared to the dead time generated by the (1–f) fraction. Thus, statistical variations in the number of f events do not have a significant affect on the percent dead time. Hence, the correlation between the f events and dead time is negligible.

Because the f events and the (1–f) events are independent random variables, the large dead time caused by the (1–f) events is seen by the f events as if someone is randomly opening and closing the gate that permits gamma-rays to be accepted for analysis in the spectrometer. As far as the f events are concerned, the available live time is a time that can be measured deterministically. If the live time and the real time are both accurately measured, then the ratio of real time to live time deterministically predicts the ratio of the number of f events that would have been counted (in the absence of dead time) to the number of f events that were able to elude the dead time caused by the (1–f) events.

Hence, the variance in r and the covariance between r and N_u is negligible in equation (10) if f is a relatively small fraction. Generally, keeping $f < 0.03$ (i.e., 3%) will limit the underestimate of the standard deviation to <10% when using the data from the Error Spectrum. This condition is easily met when integrating peaks from a Ge detector, which typically has a FWHM energy resolution <0.2% at 1.33 MeV.

Appendix B: Specific Formulae for the Corrected Spectrum and Error Spectrum

The ZDT electronics overcomes the variation of r with changing counting rates by breaking up the acquisition into live time intervals, Δt_{Lj} that are so short that the counting rate does not change significantly during that differential live time interval. For each of these j^{th} live time intervals, the differential real time to live time ratio is measured as

$$r_j = \frac{\Delta t_{Rj}}{\Delta t_{Lj}} \qquad (20)$$

Where Δt_{Rj} is the real time measured during the j^{th} differential live time interval, Δt_{Lj}. Thus, there is a stream of continually changing values r_j for the gamma-ray counts to sample as each individual gamma-ray arrives. When the k^{th} gamma ray arrives, it samples the current value of r_j and designates that value as r_k. Instead of saving this event as one count in the energy spectrum, the arrival is stored by adding r_k to the numbers already tallied in the appropriate energy channel‡. Thus, this makes the same correction as in equation (8), but on an event-by-event basis. At the end of the acquisition, the number stored in channel i of the energy spectrum is

$$N_{ci} = \sum_{k=1}^{N_{ui}} r_k \qquad (21)$$

Where N_{ui} is the number of counts destined for the i^{th} energy channel before the ZDT dead time correction is applied.

Equation (10) specifies that the variance in a sum of a series of measurements is the sum of the variances of each measurement. Consequently, an error spectrum is formed by summing the variances from each corrected count. Channel i in the error spectrum corresponds to channel i in the energy spectrum. As each gamma-ray arrives for the i^{th} channel, the sampled value r_k is squared and added to the i^{th} channel in the error spectrum, according to the guidance from equation (12). At the end of the acquisition, the number in channel i of the error spectrum will be

$$\sigma^2_{Nci} = \sum_{k=1}^{N_{ui}} r_k^2 \qquad (21)$$

Taking the square root yields σ_{Nci}, which is the standard deviation for the differentially-corrected counts N_{ci} in channel i of the energy spectrum.

Because equation (22) is used only for the normal case where the counts in a peak represent a small fraction, f, of the total counts in the spectrum, the variance in r_k is negligible. Consequently, the differential time intervals for ZDT can be based on real time or live time without significantly affecting the variance calculation. Differential live time intervals would become much longer as the percent dead time increases. This trend would make it difficult to ensure that the differential time interval is much shorter than the lifetime of the short-lived radioisotopes. Consequently, differential real time intervals are normally employed.

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