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Artifacts in Digital Coincidence Timing

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Abstract

Digital methods are becoming increasingly popular for measuring time differences, and are the *de facto* standard in PET cameras. These methods usually include a master system clock and a (digital) arrival time estimate for each detector that is obtained by comparing the detector output signal to some reference portion of this clock (such as the rising edge). Time differences between detector signals are then obtained by subtracting the digitized estimates from a detector pair. A number of different methods can be used to generate the digitized arrival time of the detector output, such as sending a discriminator output into a time to digital converter (TDC) or digitizing the waveform and applying a more sophisticated algorithm to extract a timing estimator.

All measurement methods are subject to error, and one generally wants to minimize these errors and so optimize the timing resolution. A common method for optimizing timing methods is to measure the coincidence timing resolution between two timing signals whose time difference should be constant (such as detecting gammas from positron annihilation) and selecting the method that minimizes the width of the distribution (i.e., the timing resolution). Unfortunately, a common form of error (a nonlinear transfer function) leads to artifacts that artificially narrow this resolution, which can lead to erroneous selection of the “optimal” method. The purpose of this note is to demonstrate the origin of this artifact and suggest that caution should be used when optimizing time digitization systems solely on timing resolution minimization.

Keywords

Timing resolution; artifacts; digital timing methods; timing optimization

Modern PET cameras usually employ some form of digital timing to measure the difference in arrival times of two positron annihilation photons. Most use a scheme such as shown in Figure 1, whereby the arrival times of two detector signals are digitized with respect to a common master clock, and their relative arrival time difference is found by subtracting these digital time values. With the increasing interest in time-of-flight PET [1–3], increasingly accurate measurements of this time difference are desired, which has spurred the development of more advanced digital timing systems. Examples are high precision time to digital converters (TDCs, such as the CERN HPTDC [4]) that digitize the output of a discriminator that is connected to the detector, and waveform sampling methods, whereby the leading edge of the (analog) detector output is digitized at high rate (e.g., 2–5 GHz) and a sophisticated numerical algorithm used to extract a timing estimator from the digitized waveform [5, 6].

Unfortunately, this digitization process is rarely perfect, which can lead to artifacts. These imperfections are described by the transfer function, which is defined as the correspondence between the true arrival time and the measured arrival time (for a single gamma). The ideal transfer function is the line of identity ($\text{Measured_Time} = \text{True_Time}$), but non-ideal performance of the digitization electronics or algorithm results in a transfer function that deviates from linear. When this happens (Figure 2a), some portions of the transfer function slope will be less than one, and events that occur closely together in time in this region will have a measured time difference that is less than their true time difference (e.g., the pair of vertical lines, representing a pair of detections separated by a small time, with True Times near 800 ps in Figure 2a). If there are regions with a slope less than one, there must also be regions where the slope is greater than one, and these regions yield measured time differences that are artificially greater than their true time difference (e.g., the pair of vertical lines with True Times near 200 ps in Figure 2a). As shown in Figure 2b, this tends to result in a distribution where the central coincidence peak becomes artificially narrow but the tails are broadened. The data in 2b were generated with a Monte Carlo simulation whereby annihilation photons were assumed to interact simultaneously (at a random time during the clock period, taken to be 1 ns) in the two detectors being struck, and each detector has an intrinsic timing resolution of 100 ps FWHM. The transfer function is used to convert the “true” time of the hit (as generated by the detector) into a measured detection time for each gamma, 5×10^6 realizations are generated, and the measured time difference for each gamma pair histogrammed in 1 ps bins.

For the perfect transfer function, the timing distribution is Gaussian with a FWHM of $100 \text{ ps} \times \sqrt{2}$, as expected. For the distorted transfer function, some of the events are measured to be closer in time than they truly are, which enhances and artificially narrows the coincidence peak. While a similar number of events are measured to be further apart (in time) than they truly are, these events tend to create a relatively broad, but low amplitude “tail” on the timing distribution. Thus, the timing distribution still contains a distinct peak, but is no longer Gaussian. But because of the nature of the FWHM function, its “measured” FWHM is invariably smaller than the true FWHM!

This effect is seen for many different types of distortion in the transfer function. Figure 3 shows the transfer function and the coincidence timing distribution for several different shapes of transfer function distortions. It is clear that relatively small distortions in the transfer function yield significant “improvements” in the measured coincidence timing resolution and that many different shapes of transfer function distortion narrow the FWHM.

However, not all types of transfer function distortion result in this behavior. In the examples given in Figure 2 and 3, the distortions have long-range correlations over periods of time that are similar to or longer than the timing resolution (i.e., 100 ps). Such distortions can result from clock feedthrough, systematic errors in calibration, or incorrect methods for merging information in “hybrid” digitization approaches (where the most and least significant bits are provided by different approaches, such as a clock and counter for the most significant bits and vernier for the least significant bits [7]). This type of distortion tends to produce a timing distribution that has a single peak that, while not Gaussian, is smooth, monotonic, and generally pleasing to the eye.

If, on the other hand, the distortions do not have long-range correlations, but instead have only short-range correlations (or are uncorrelated), the pronounced narrowing of the timing resolution does not occur. To demonstrate this, we simulated a case for which there are distortions, but no correlations. For this simulation, the true width of each timing bin was equal to its nominal width of 1 ps plus a random number whose value was taken from a Gaussian distribution with a 0.5 ps FWHM. Such a pattern would occur if the TDC differential non-linearity followed a Gaussian distribution. Although there is a very slight enhancement (~5%) in the timing distribution near a time difference of zero, the distribution is virtually indistinguishable from the correct distribution and the FWHM is within 3% of the proper value (137.5 ps FWHM for the distorted function versus 141.4 ps for the perfect transfer function).

Generally speaking, the way to eliminate all of these distortions is to ensure that the transfer function is “perfect” by properly calibrating the TDCs. While this is conceptually trivial (and essentially tautological), it is much harder to achieve, as undetected systematic errors can easily creep into calibration procedures and algorithms. While a multitude of calibration methods have been described, a common calibration method is to histogram the digitized times of pulses that are randomly distributed in time, and correct so that a uniform distribution is obtained (e.g., [8]). However, events that are uniformly distributed in time are surprisingly difficult to obtain, especially if the system has any dead time. We also note that both incorrect transfer functions and calibration imperfections are likely to result in non-Gaussian shapes for the timing distribution, and that detecting deviations from a Gaussian shape may be a useful method for identifying such problems.

We believe that this effect is likely to become more noticeable by the community as the timing resolution of time-of-flight PET improves. For example, the investigation reported herein was prompted by our characterization of the Tachyon, a time-of-flight PET camera with 314 ps FWHM timing resolution [9] whose electronics [10] uses the CERN HPTDC [4]. As we developed calibration methods, we noticed that while our measured timing resolution changed by nearly 50 ps FWHM, the results did not necessarily correlate with what we believed to be the accuracy of our calibration method!

Thus, when seeking to optimize digital time extraction methods, one should not concentrate solely on the timing resolution, as imperfections can artificially reduce this number. Instead, it is prudent to also seek ways of confirming that the TDC is accurately calibrated before performing such optimization.

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Figure 1.

Typical Timing Diagram. The times between the rising edge of the Clock signal and the rising edges of the signals from Detector 1 and Detector 2 are independently digitized. The time difference Δt between the two detector signals is subsequently computed by subtracting these digital time values.

Figure 2.

Left) Perfect vs. Distorted Transfer Function. When two events are measured where the slope of the distorted transfer function is >1 (near 200 ps True Time), the measured time difference is greater than the true time difference. When the slope is <1 (near 800 ps True Time), the measured time difference is less than the true time difference. Right) Coincidence timing spectrum using the perfect and distorted transfer functions. The distorted one produces a smaller FWHM but higher tails.

Figure 3.
Examples of distorted transfer functions (left) and the resulting distribution of time differences (right) for both the distorted and undistorted transfer functions.