IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 38, NO. 2, APRIL 1991

First Photoelectron Timing Error Evaluation of a New Scintillation Detector Model

Nicholas Petrick, Neal H. Clinthorne, W. Leslie Rogers and Alfred O. Hero III
The University of Michigan, Division of Nuclear Medicine and
Department of Electrical Engineering and Computer Science.
Ann Arbor, MI 48109-0552

Abstract

In this study, a general timing system model for a scintillation detector developed in Hero, et al. [1] is experimentally evaluated. The detector consists of a scintillator and a photodetector such as a photomultiplier tube or an avalanche photodiode. The model uses a Poisson point process to characterize the light output from the scintillator. This timing model was used to simulate a BGO scintillator with a Burle 8575 PMT using first photoelectron timing detection. Evaluation of the model consisted of comparing the RMS error from the simulations with the error from the actual detector system. We find that the general model compares well with the actual error results for the BGO/8575 PMT detector. In addition, the optimal threshold is found to be dependent upon the energy of the scintillation. In the low energy part of the spectrum, we find a low threshold is optimal while for higher energy pulses the optimal threshold increases.

I. Introduction

There has been recent interest in finding a practical model for scintillation detectors. Such a model is needed to find optimal estimators [1] and fundamental performance limits [2] of coincidence timing in Positron Emission Tomography (PET) Time of Flight (TOF) detection systems. The model must be able to describe the gamma ray interaction in the scintillator along with the gain associated with the photodetector but be simple enough for efficient implementation.

Recently, a Poisson/Gaussian superposition model has been proposed for the output current of a scintillation detector [1,3]. Based on this model, lower bounds on estimator performance have been derived and the maximum likelihood estimation strategies have been developed. The goal of this study is to experimentally evaluate the validity of this model. The performance criterion of interest in TOF systems is the RMS timing error. The model evaluation is done by comparing the predicted first photoelectron timing (FPET) error using the model with the actual error measured from a BGO/Burle 8575 scintillation detector.

*This work is supported by the National Cancer Institute, DHHS, under grant CA46622.

II. Scintillation Detector Model

A. Model Description

The physical process we would like to describe is the interaction of a high energy gamma ray with a scintillation crystal and the subsequent multiplication statistics of the photodetector. In response to an incident gamma ray, the scintillator emits a large number of lower energy visible photons. The scintillator is coupled with a photodetector such as a photomultiplier tube (PMT) or an Avalanche Photodiode (APD). The photodetector converts the photons emitted by the scintillator into photoelectrons and amplifies them, producing an output current. The important processes that characterize the output current are (1) the photon distribution created by the scintillator from an incident γ-ray, (2) the single electron response (SER), (3) the photomultiplication gain and (4) the thermal noise of the photodetector. We incorporate these processes into the general model:

$$I(t) = \sum_{j=1}^{N(t)} g_j p(t - t_j) + W(t) \tag{1}$$

where the output current $I(t)$ is just the superposition of the multiple single electron response functions $p(\cdot)$ plus the thermal noise. The photodetector gain g multiplies the SER and is assumed to be an independent and identically distributed (iid) random process. The thermal noise is described by the additive white noise process $W(t)$. The final process that must be incorporated is the photon arrival process. The photon arrival times $\{t_i\}_{i=1}^{N(t)}$ produced by a single γ-ray interaction are determined using an inhomogeneous Poisson process $\{N(t)\}$ [1]. This random process has a mean intensity function given by:

$$\lambda(t) = \lambda_s(t - \tau) + \lambda_o \tag{2}$$

where $\lambda_s(\cdot)$ and λ_o are the known optical signal and dark current intensities respectfully. This model becomes useful in Monte Carlo simulations because the different parameters and probability distributions can be measured for each type of scintillation detector.

0018-9499/91/0400-0174$01.00 © 1991 IEEE

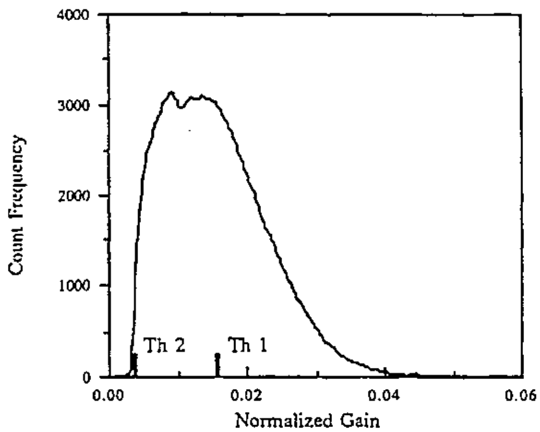

Figure 1: The Burle/RCA 8575 single photoelectron gain distribution along with the FPET discriminator thresholds.

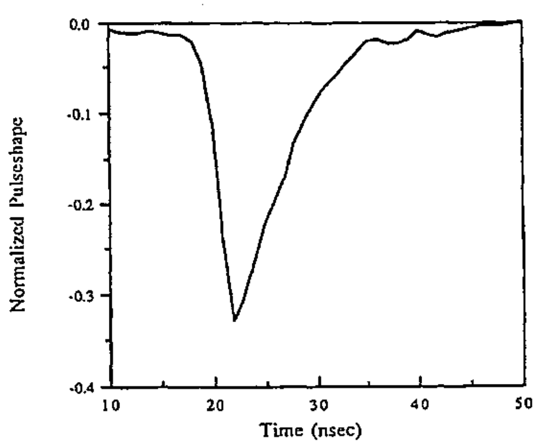

Figure 2: The mean single electron response of the Burle/RCA 8575 photomultiplier.

B. Model Parameters and Random Processes

The scintillation detector used in this experiment was a BGO scintillator connected to a Burle/RCA 8575 PMT. The PMT gain distribution was found for the 8575 tube by sampling the peak of the single photon response and is described in [4]. The mean SER of the PMT was measured by sampling the PMT output with a fast digitizer and is described in [2]. The gain distribution and mean SER are shown in figures 1 and 2 respectively. The thermal noise $W(t)$ was assumed to be negligible for ideal first photoelectron timing, leaving only the photon intensity function to be calculated. A triexponential intensity function was used for the BGO scintillator with a rise time of 2.8 nsec and a quick decay of 60 nsec along with a longer 300 nsec decay component [5]. The 300 nsec decay makes up 90% of the total light while the 60 nsec component corresponds to the remainder. The intensity function is shown in figure 3. Now with the measured SER and probability distributions of the BGO/8575 detector, the system can be simulated.

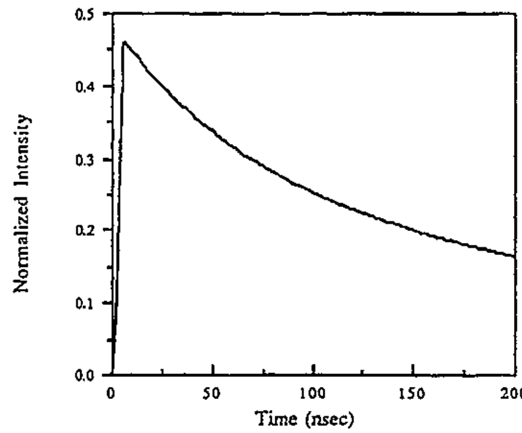

Figure 3: The intensity function for a BGO scintillator used to determine the photon arrival times.

III. First Photoelectron Timing Performance

A. Monte Carlo Simulation

A Monte Carlo simulation was performed on a Decstation 3200 to determine the first photoelectron timing performance of a BGO/8575 scintillation detector. The simulation was done by first creating the simulated output current and then applying a threshold detector. The output current was created by generating the photon arrival times in 1 nsec bins from the Poisson point process with intensity $\lambda(t)$. Random gains chosen from the 8575 gain distribution were then applied to this photon arrival data giving the desired output current. An estimate was determined for each γ-ray as the time of the first threshold crossing. The simulations were done using both the high and low thresholds shown in figure 1 and the RMS error

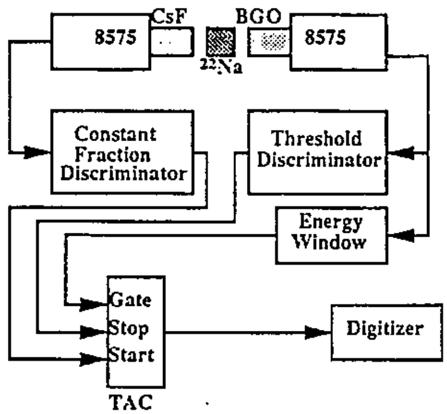

Figure 4: The experimental apparatus for measuring the first photoelectron timing error.

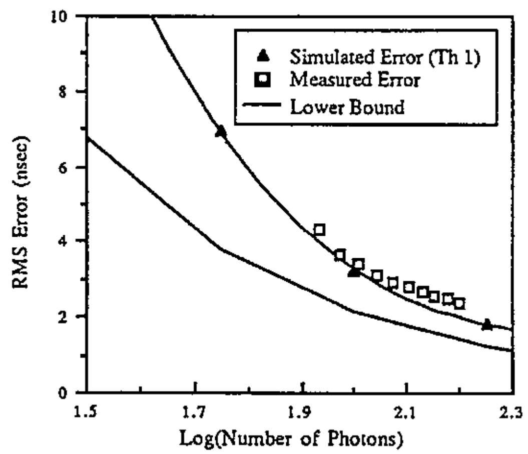

Figure 5: Simulated and measured first photoelectron timing errors for the BGO/Burle 8575 scintillation detector.

was calculated based on 200 independent trials. An actual BGO/8575 detector was than used to measure the real errors for comparison purposes.

B. Experimental Measurement

A first photoelectron timing system was set up using a cylindrical BGO scintillator and a Burle/RCA 8575 Photomultiplier. The BGO scintillator was 1 inch in diameter and 1 inch high. This system is shown in figure 4. A CsF detector along with a constant fraction discriminator with a measured timing error of 500 psec was used as a starting reference for the time-to-amplitude converter (TAC). The stop pulse was generated by a threshold discriminator connected to the output of the BGO/8575 detector. To eliminate non-scintillation events from the timing error, the TAC was gated with an energy window. The output

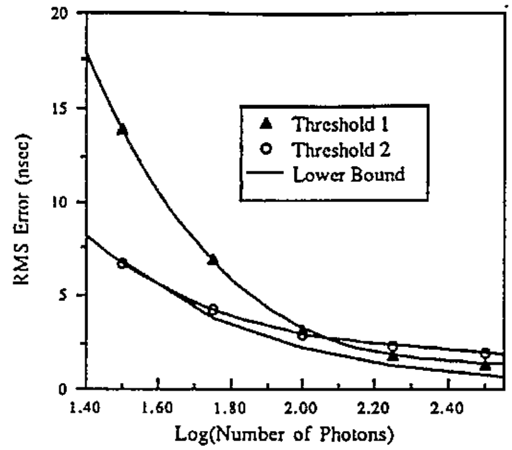

Figure 6: Simulated first photoelectron timing errors for high and low discriminator thresholds.

of the TAC was used as the FPET timing estimate and digitized with an A/D converter. The RMS error was then calculated as a function of the number of photons detected by the PMT by shifting a 0.1 volt energy window across the photopeak. This error is plotted in figure 5 along with the RMS error from a simulated system. Figure 5 also contains the fundamental lower bound found in [2]. Figure 6 shows the simulated results using both a high and low threshold along with the lower bound.

C. Comparison of FPET Error

From the result in figure 5, we see that even with the ideal conditions used in (1) the first photoelectron timing error from the simulations compares quite well with the actual error measured. The major difference between the real and simulated error is that the real error does not fall off as rapidly as the simulated error in the high photon region. The RMS error measurement was based on over 25,000 sample points and the maximum deviation measured in repeated experiments was only 170 psec. This small deviation in the RMS timing error does not explain the slow fall off seen in figure 5 when we have a large number of photons. This result may be due to using the 2.8 nsec risetime in the photon intensity function. When looking at the true output of the BGO/8575 scintillation detector, the rise time was measured to be ~4.5 nsec. With a longer rise time, we would expect to see this slow fall off. Another possible explanation for the discrepancy between the measured and simulated error may be that the photon arrival process is not truly Poisson. This non-Poisson nature is due to dispersion in the crystal introducing dependencies among the secondary emissions [5]. We can see from figure 6 that the optimal threshold for minimizing the RMS error is not constant, but rather a function of the number of photons emitted by the scintillator. As the number of photons increases a larger threshold is needed to minimize the RMS error. This result is not surprising since with a larger threshold the time estimate is taken at the center of the steep rising edge instead of the noisy start as with a low threshold.

IV. Conclusion

The scintillation detector model developed by Hero, et al. was experimentally evaluated. The FPET error results show that this model can be used to accurately simulate the timing performance of the BGO/8575 scintillation detector. The model structure is quite general, making it applicable to simulations using different types of scintillators or photodetectors by using their corresponding intensity, gain, single electron response and noise functions. The timing simulations also showed that to find the minimum error threshold it is important to determine the number of photons being emitted by the scintillator crystal.

References

[1] Hero A. O., N. Antoniadis, N. H. Clinthorne, W. L. Rogers and G. D. Hutchins, "Optimal and Sub-Optimal Post-Detection Timing Estimators for PET," *IEEE Transactions on Nuclear Science*, 37, No. 2, 725-729, April 1990.

[2] Clinthorne N. H., N. Petrick, W. L. Rogers and A. O. Hero, "A Fundamental Limit on Timing Performance with Scintillation Detectors," *IEEE Transactions on Nuclear Science*, 37, No. 2, 658-663, April 1990.

[3] Hero A. O., "Timing Estimation for a Filtered Poisson Process in Gaussian Noise," *IEEE Transactions on Information Theory*, To appear January 1991.

[4] *RCA Photomultiplier Handbook*, pp. 59-60, RCA, Lancaster, PA, 1980.

[5] Moszynski M., C. Gresset, J. Vacher and R. Odur, "Timing Properties of BGO Scintillator," *Nuclear Instruments and Methods*, 34, 403-409, 1981.