An Investigation of Waveform Sampling for Improved Signal Processing in TOF PET

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Abstract—The development of fast photodetectors and of fast, high light output scintillation crystals has placed an increased emphasis on the need for fast readout electronics used for Time-Of-Flight (TOF) PET detectors. These improvements have paralleled developments in analog sampling technology that makes fast waveform digitizing of photodetector signals an attractive alternative to custom PCB and IC designs. Waveform digitization offers a flexible means for evaluating and implementing more complex signal processing algorithms. We used a commercial 1GHz 2Gs/s waveform digitizing system to acquire coincident pulses from LYSO and LaBr$_3$ (5%Ce) scintillator crystals coupled to a fast PMT. By measuring the time pickoff based on a linear fit to the rising edge of the pulse, we show an improvement in coincident timing resolution from ~200ps to ~80ps FWHM for LaBr$_3$(5%Ce) coupled to Photonis XP20D0 PMTs, and from ~160ps to ~80ps Full Width at Half Maximum (FWHM) for LaBr$_3$(5%Ce) coupled to Hamamatsu H4998 PMTs. Our results show a consistent improvement in timing resolution as well as reduced sensitivity to signal risetime as compared to leading edge (LE) pickoff techniques. Measurements with partial detector modules indicate that system timing resolution of <200ps is attainable with LaBr$_3$ (5%Ce) pixeled detectors designed for TOF PET.

I. INTRODUCTION

The timing resolution of scintillator detectors is determined by the combined effect of the scintillator’s intrinsic light emission characteristics, the light transport in the crystal, detector geometry, the photodetector response and the readout electronics. Coincident timing resolution of ~200ps FWHM has been measured with small samples of LaBr$_3$(5%Ce) coupled directly to a Photonis XP20D0 PMT, using a risetime compensated Leading Edge (LE) discriminator. Measurements taken with 4x4x30mm LaBr$_3$(5%Ce) pixels have shown a degradation in timing resolution to 240ps FWHM, while measurements with a LaBr$_3$(5%Ce) pixel array coupled to hexagonally packed XP20D0 PMTs via a lightguide have yielded a timing resolution of 313ps, FWHM [1]. When implemented in a full system, the same pixeled array detector design yields a timing resolution of 376ps FWHM [2], averaged across all detector pairs. This loss is likely due to non-optimized calibrations of PMT gains and timing offsets.

However the degradation in measured timing resolution from a small crystal coupled directly to a PMT to a pixeled array can be partially explained by the scintillation light transport in the crystal, reduced light collection in the detector and non-uniformities in PMT response. A significant contributor to the timing resolution is the LE time pickoff method, commonly used in commercial and prototype TOF PET systems [2]. LE time pickoff will vary systematically with pulse shape and signal amplitude. Furthermore, the single sample time estimate of a LE discriminator will be sensitive to noise on the photodetector signal [3], electronic noise and variation in the baseline which effectively modulate the LE threshold, resulting in dispersion in time pickoffs. In a detector with light sharing, the decreased light in each photodetector decreases the signal to noise ratio, further degrading the attainable timing performance. LE time pickoff also introduces sensitivity to photodetector risetime, since the noise on the signal translates to time jitter in direct proportion to the slew rate of the signal at the LE threshold level.

One way to reduce the LE associated effects is by determining a time pickoff based on more information from each pulse. Waveform digitization offers a means for extracting the arrival time of the event by taking into account the information encoded in the full waveform and correcting for the effect of pulse pile-up on the waveform baseline. A pickoff algorithm based on the sampled waveform will be less susceptible to noise than a simple sample time estimate, such as a LE discriminator, and will allow us to use measured information about the pulse shape in determining the time pickoff.

We present timing resolution measurements obtained by analyzing digitized waveforms from coincident detectors. In section II, some considerations in sampling technique are presented. Section III presents the time pickoff algorithm, factors in its optimization and verification of the system timing calibration. Sections IV and V respectively present the single PMT and PMT array detector timing results. Sections VI and VII discuss the results and future work.

II. SAMPLING IN TIME DOMAIN

Signal sampling in the time domain allows us to reconstruct the signal, obtain a time pickoff, integrated energy and a baseline estimate. Furthermore, subtle systematic variations in the pulse shape can be quantified and correlated with physical processes such as DOI and inter-crystal scattering.
In order to fully reconstruct the signal, the signal must be sampled at the Nyquist rate [4], i.e. twice the fastest frequency component of the photodetector signal:

\[ f_{\text{sampling}} = 2\nu_{\text{max}} \quad (3) \]

For a signal with a 10%-90% risetime of \( T_{10\%-90\%} \), the high frequency cutoff, or bandwidth [5], will be:

\[ \nu_{\text{max}} = \frac{0.349}{T_{10\%-90\%}} \quad (4) \]

For a Hamamatsu H4998 PMT, with a 0.7ns 10%-90% risetime, the signal bandwidth will be ~500MHz and the required sampling rate will be ~1Gs/s; for a Photonis XP20D0 PMT [6], with a 2.5ns risetime, the signal bandwidth will be ~135MHz and the required sampling rate will be ~270Ms/s. Obersampling of the signal allows a reduction in the approximation error due to the finite resolution of each sample in Digital Signal Processing (DSP) and is thus practically beneficial [7]. To capture the signal, the front end bandwidth of the acquisition system must be as fast at the fastest component of the photodetector signal. Faster frequency components will be the result of EMF pickup and noise processes in the electronics, and contain little or no information about the light pulse. Analog signal shaping will prevent error due to aliased capture of these noise processes.

The integrated energy can be determined by summing the signal samples over the desired integration time. Waveform sampling also offers a simple way for pulse by pulse correction for baseline shifts due to pulse pile-up.

Fig. 1. Persistence plot of photopeak pulses from a LaBr\(_3\)(5%Ce) crystal coupled to a H4998 PMT. Signals were acquired with an Agilent DC271 digitizer at a sampling rate of 2Gs/s, through a 700MHz analog bandwidth limit.

Fig. 2. Energy spectrum for a LaBr\(_3\)(5%Ce) crystal coupled to a XP20D0 PMT. Signals were acquired with an Agilent DC271 digitizer at a sampling rate of 2Gs/s, through a 200MHz analog bandwidth limit. Event energy was determined by summing the signal samples over 60ns and subtracting the event baseline.

III. TIME PICKOFF ALGORITHM

The reconstructed waveform captures all the information from the analog waveform, and thus any algorithm implemented in analog electronics may be applied to the digitized waveform. In order to determine the arrival time of the pulse, we can make use of more information than a single sample, as in LE discrimination. The increased sampling of the signal reduces the susceptibility to noise of the resulting time pickoff. Use of multiple data points in determining the time pickoff allows the consideration of data from later photons. The later photons carry greater timing uncertainty, and can be weighted accordingly in determining the time pickoff. The pulse shape information allows us to estimate the pulse arrival time, reducing the susceptibility of the pickoff estimate to the rising edge slew rate and to variations in it. This reduces the need for photodetectors with fast risetimes, in so far as the photodetector risetime affects the time pickoff algorithm.

Fig. 3. Plot of a photopeak pulse from a LaBr\(_3\)(5%Ce) crystal coupled to a XP20D0 PMT. Signal was acquired at with an Agilent DC271 digitizer at a sampling rate of 2Gs/s, through a 700MHz analog bandwidth limit. The plot shows a linear fit to the first 6 points on rising edge of the pulse. The equation for the linear fit is given along with a goodness of fit estimate.

A simple time pickoff algorithm assumes a first order polynomial fit to the rising edge, assigning equal weight to
The time pickoff is determined as the crossing point of the linear fit to a measurement of the baseline. Pulse-by-pulse estimation of the baseline allows for reduced sensitivity to random fluctuations in the baseline as well as to event pile-up.

We used an 8-bit Agilent Acquisir DC271 cPCI digitizing system, operated at 2Gs/s. The analog front-end bandwidth was set above the bandwidth of the photodetector used, at 700MHz and 200MHz for the H4998 and XP20D0 PMTs, respectively. The analog bandwidth was chosen in accordance with the options available with the Acquisir digitizer hardware. The system was triggered based on a coincidence determination using NIM discriminators and a coincidence module:

The arrival time of each PMT signal with respect to the system trigger was determined using the linear fit to the rising edge, as described. The arrival times of each pair of coincident pulses were subtracted, and the FWHM of the resulting coincidence time difference distribution was measured.

The digitizer’s timing calibration was verified by measuring the coincidence time difference between two detectors, each comprising of a LaBr₃(5%Ce) crystal coupled to a XP20D0 PMT. Coincident time differences were recorded for three source positions, $x_1=0$, $x_2=2.54\text{cm}$, $x_3=7.62\text{cm}$, resulting in centroid time shifts of $65.4\text{ps/cm}$, in good agreement with $66.7\text{ps/cm}$ expected from $2(\Delta x)/c$.
IV. SINGLE CRYSTAL/PMT RESULTS

Implementing the time pickoff algorithm described, we measured the coincident time difference resolution for several scintillator and PMT configurations. The results are compared with coincidence timing measurements taken with a LeCroy 825Z risetime compensated fast timing discriminator digitized by a 25ps/bin C414 Caen Time to Digital Converter (TDC).

![Image](image1.png)

Fig. 8. Schematic representation of coincident detectors used for timing measurement.

TABLE I: LEADING EDGE AND DSP TIMING RESOLUTIONS FOR SINGLE PMT DETECTORS

<table>
<thead>
<tr>
<th>Measurement</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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</thead>
<tbody>
<tr>
<td>Detector 1</td>
<td>LaBr(5%Ce) cylinder +XP20D0 PMT</td>
<td>LaBr(5%Ce) cylinder +H4998 PMT</td>
<td>LaBr(5%Ce) cylinder +H4998 PMT</td>
<td>LaBr(5%Ce) cylinder +H4998 PMT</td>
<td>LaBr(5%Ce) cylinder +H4998 PMT</td>
</tr>
<tr>
<td>Detector 2</td>
<td>LaBr(5%Ce) cylinder +XP20D0 PMT</td>
<td>LaBr(5%Ce) cylinder +XP20D0 PMT</td>
<td>LaBr(5%Ce) cylinder +XP20D0 PMT</td>
<td>LaBr(5%Ce) cylinder +H4998 PMT</td>
<td>LYSO pixel +H4998 PMT</td>
</tr>
<tr>
<td>DSP Coinc. Tres(ps)</td>
<td>76±4</td>
<td>81±4</td>
<td>80±4</td>
<td>116±4</td>
<td>133±5</td>
</tr>
<tr>
<td>LE Coinc. Tres(ps)</td>
<td>196±10</td>
<td>180±10</td>
<td>164±10</td>
<td>240±10</td>
<td>310±10</td>
</tr>
</tbody>
</table>

(b) FWHM of coincident time pickoff difference measured with waveform fitting and with risetime compensated discriminator.

V. DETECTOR RESULTS

In order to test the waveform fitting methodology in a light sharing detector configuration, we placed a LaBr(5%Ce) crystal above the gap between three PMTs in hexagonally packed array of XP20D0 PMTs. At this position light collection is reduced as compared to a crystal positioned over a PMT center, and thus offers a worst-case scenario for timing performance in such a detector.

![Image](image2.png)

Fig. 9. Schematic of coincident detector setup used for light sharing detector measurement. Reference detector is LaBr(5%Ce)/XP20D0. For light sharing detector, LaBr(5%Ce) crystal was placed above gap position between three PMTs.

The coincident timing resolution of each of the three PMT signals vs. the reference detector was measured using a risetime compensated LE discriminator, as well as with the digitized waveform fitting algorithm. An analog sum of the signals from the three PMTs was generated using an ORTEC AN308/NL mixer, with 80MHz front-end bandwidth. The analog sum was used to generate a LE time pickoff as well as a DSP waveform fitting time pickoff. See Table II.

Table II. Compensated leading edge and waveform fitting timing resolution results for a LaBr(5%Ce) crystal at the PMT gap position. The timing resolution was measured using a risetime compensated leading edge discriminator as well as waveform fitting. The timing resolution of each PMT signal vs. the reference detector was measured separately, each PMT collecting ~1/3 of the total collected light. The timing resolution of the analog sum of the three PMTs was then measured vs. the reference detector.

![Image](image3.png)

TABLE II: LEADING EDGE AND DSP TIMING RESOLUTIONS FOR PMT ARRAY

<table>
<thead>
<tr>
<th></th>
<th>LE</th>
<th>DSP</th>
</tr>
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<tbody>
<tr>
<td>PMT1</td>
<td>564ps</td>
<td>112ps</td>
</tr>
<tr>
<td>PMT2</td>
<td>571ps</td>
<td>110ps</td>
</tr>
<tr>
<td>PMT3</td>
<td>452ps</td>
<td>135ps</td>
</tr>
<tr>
<td>Analog sum</td>
<td>277ps</td>
<td>104ps</td>
</tr>
</tbody>
</table>

VI. DISCUSSION

The results show consistently better timing results with DSP over those obtained with the compensated LE discriminator. The improvement in coincident timing resolution for the higher Quantum Efficiency (QE) 2.5ns risetime XP20D0 PMT was more significant than that measured with the 0.7ns risetime H4998 PMT.

The timing resolution measured with waveform fitting was consistently less sensitive to light collection than the LE measurement. Reducing the collected light by a factor of 3 resulted in degradation in timing resolution from 104ps to ~120ps (Table II). The same decrease in light collection, and corresponding decrease in signal to noise for the LE discriminator resulted in a degradation in timing resolution from 277ps to ~530ps. Similarly, the degradation in timing resolution for the LYSO pixel compared to the LaBr(5%Ce) pixel is 133ps vs. 116ps, as compared to 310ps vs. 240ps for LYSO and LaBr(5%Ce) using LE discriminators. LYSO exhibits ~0.5 the light output of LaBr(5%Ce), with ~x2 the decay constant, leading to a signal amplitude of ~1/4 of that generated by LaBr(5%Ce) and a corresponding factor of 4 decrease in signal to noise. The impact of the decreased signal to noise affects the LE timing results in a more significant manner than it affects the DSP waveform fitting results.

The results obtained with the PMT array demonstrate the improved timing resolution attainable with DSP waveform fitting in a TOF PET detector. Based on the coincident detector measurements, the degradation in timing resolution from a small LaBr(5%Ce) crystal on a single H4998 PMT to a
LaBr$_3$(5%Ce) pixel on a single PMT is $((116^2-80^2)^{1/2}=84$ps FWHM. So, replacing the small crystal from the array measurement (Table II) with a pixel would degrade the DSP timing resolution to $(104^2+84^2)^{1/2}=134$ps, or $(134^2-76^2)^{1/2}=123$ps FWHM when deconvolving the contribution of the reference detector. A projected timing resolution for coincident pixelated detectors would be $123*2^{1/2}=174$ps. This projection is for a crystal positioned above the gap position in the hexagonally packed PMT array, where light collection is poorest, and does not correct for the contribution of the analog summing unit to the timing resolution.

VII. CONCLUSIONS AND FUTURE WORK

DSP waveform fitting offers a way of achieving superior timing measurements as compared to those attainable by LE discrimination. The improvement in timing performance is evident in single crystal/photodetector configurations, as well as in a PET detector with light sharing to achieve crystal encoding. The reduced sensitivity to noise and photodetector risetime increase the need for higher QE photodetectors over fast risetime photodetectors using DSP time pickoff technique. Future work will focus on improving the DSP acquisition and time pickoff algorithm. The differences in quality of the timing information encoded in different parts of the waveform will be weighted in the pickoff algorithm. Depth dependent variations in the waveform shape will be explored as a way for obtaining a DOI correction to the time pickoff.

The timing performance of a pixelated Anger logic PET detector will be further investigated. The timing performance attainable with different scintillator and photodetector combinations will be further explored.

REFERENCES