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Analysis of Digital Waveform Methods with DRS4 Evaluation Board

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Abstract: Various digital methods were examined for determining the relative arrival times of pulses from ϕ20 mm × 5 mm $LaBr_3$ scintillators. In this study, pulses from the photomultiplier tubes (PMTs) were digitized by DRS4 evaluation board, a switched capacitor array (SCA) produced by the Paul Scherrer Institute (PSI). The high bandwidth, low power consumption and short readout time make DRS4 attractive for many experiments, replacing traditional ADCs and TDCs. The sampling signals were post processed with multiple techniques. These techniques include: (1) constant-fraction discrimination (CFD), (2) pulse-shape fitting, (3) mean PMT pulse model and (4) median filtered zero crossing method. The implemented CFD in the digital regimes did not improve the resolution of using analog equipment with average time resolution. The pulse-shape fitting yielded as good resolution as digital CFD, however, is much more time consuming. The median filtered method were easy to implement, and had a resolution on the order of sampling time. Average timing resolutions of 195.4 ps were obtained with mean PMT pulse model, which is better than the analog constant-fraction-zero-crossing with average resolution of 254.7 ps.

Key words: $LaBr_3$; DSR4; time resolution

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1 Introduction

Digital methods are being used more often to analyze detector signals. Advantages include: reduce drift, archiving of data for later analysis, and better control over analysis parameters. Analog methods also have advantages since they are not limited, as digital methods are, by quantization in time and amplitude.

DRS4[1], the fourth version of Domino Ring Sampler (DRS), is produced by the Paul Scherrer Institute (PSI), and is capable of digitizing 9 differential input channels at sampling rates of up to 6 Giga-samples per second (GSPS) with an analogue bandwidth of 950 MHz (-3 dB). A lot of experiments, including cosmic γ ray detector and PET scanners, replace traditional ADCs and TDCs with DRS4, because it has high bandwidth, low power consumption and short readout time.

The DRS4 evaluation board was used as an acquisition platform to gather waveforms from detectors, four different ways were implemented to process the timing information after acquisition.

In this paper, the various digital and analog methods of determining the difference in arrival time of two coincidence ^{22}Na γ-rays detected by two $LaBr_3$ detectors are compared. The analog method used the constant-fraction-zero-crossing technique. The digital technique included: (1) constant-fraction discrimination (CFD)[2–4], (2) pulse-shape fitting[5], (3) mean Photomultiplier Tubes(PMTs) pulse model[4] and (4) median filtered zero crossing method[4]. Each test using the corresponding method was done in multiple times to optimize the parameters for the best resolution and accuracy.

The difference of the calculated arrival times were

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plotted as a histogram and fit with a Gaussian distribution. The full-width at half maximum (FWHM) of the fit was used as the resolution.

1.1 Constant-faction zero-crossing

The first method is a digital version of the analog CFD zero-crossing technique. Fig. 1 shows the CFD results of the experiment data. The original signal is delayed, amplified, inverted, and then added to the original signal. This process, when optimized, transforms the unipolar signal into a bipolar pulse. The bipolar pulse crossed the time-axis at a constant faction of the height of the original pulse. The crossing time was linearly interpolated if it occurred between time-steps.

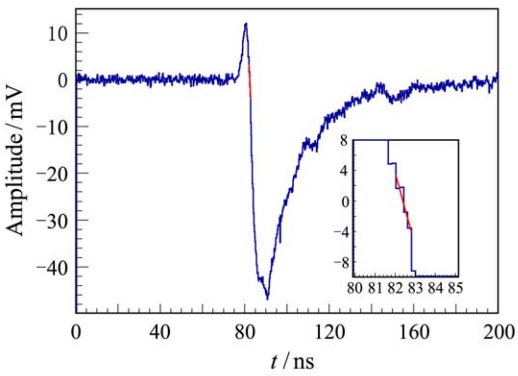

Fig. 1 (color online) An example of a CFD output generation. PMT signal digitized by DRS4 was used to generate the CFD output. In the inset, the zero crossing of the CFD output was found to be time stamp.

1.2 Pulse-shaping fitting

The signal pulse heights were obtained by integrating the charge of the DRS4 cells. 90% of the signal charge is contained in ∼ 40 ns (200 cells). Fig. 2 shows distributions of the integrated charge acquired by DRS4. The peaks corresponding to the ^{22}Na positrons annihilation are clearly seen. The mean peak values were normalized to the 511 keV energy deposited by photons. The peaks were approximated by Gaussian distribution with FWHM < 5%. The signal below 400 keV are attributed to Compton scattered photons.

Events in the 511 KeV peak were used for the TOF analysis. The pulse leading edge, up to 70% of the peak height, is well fit with a Gaussian function, as shown in Fig. 3. Using the fit parameters, the time on the leading edge corresponding to 10% of the signal amplitude height can be found:

$$T_{(i=1,2)} = 0.1\exp[-0.5(t-T_{\max})^2/\sigma_T^2] \ , \qquad (1)$$

where $T_{\max}$ is the time of the signal amplitude maximum, and σ_T is sigma of the Gaussian fit. T_1 and T_2 are the time stamp for the signal in the channel 1 and 2, respectively.

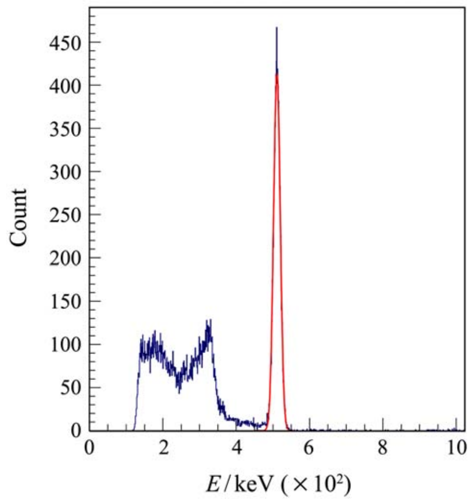

Fig. 2 (color online) Energy spectra from the $LaBr_3$ on Photonis XP20D0 acquired by DRS4. The energy resolution was less than 5% (FWHM).

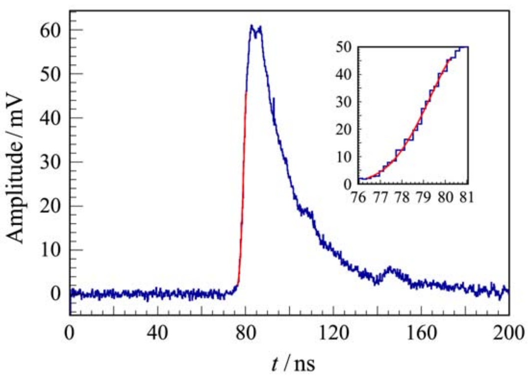

Fig. 3 (color online) The result of pulse-shaping fitting to the random PMT signal digitized by DRS4. In the inset, the fit result was used as the time stamp for PMT signal.

1.3 Mean PMT pulse model

1.3.1 Model generation

Before the raw PMT signals were analyzed, the raw PMT signals were lined up at a certain time point and summed up sample by sample. Then, the mean PMT signal, standard deviation and coefficient of variation (standard deviation/mean) for each sample were calculated. The two mean PMT signals were used as a model in this method to find the time mark for the qualified events.

1.3.2 Fitting the model

After the models are determined, a ROOT fit program was implemented to find the time mark based on a least square method for each energy qualified event.

Since the minimum value of the coefficient of variation was determined to be close to the rise time of the PMT pulse, starting position of the model and the total number of the points in the model were optimized around that region. Fig. 4 shows an example of how the model fits to a random PMT pulse to find the time stamp.

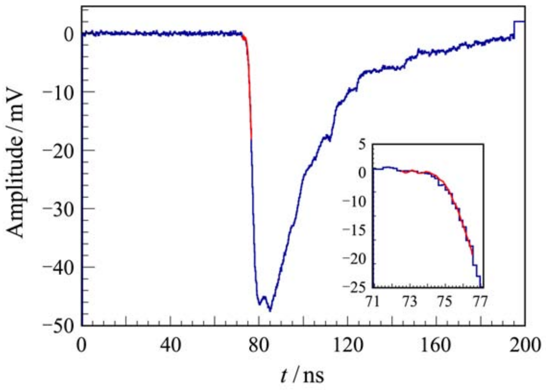

Fig. 4 (color online) The result of mean PMT pulse model fitting to the PMT signal. When the sampling rate was reduced, a simple linear interpolation was used to fill the missing samples. The result of mean PMT pulse model fitting shown in the inset was used as time stamp.

It is worth pointing out that when the sample rate was reduced, the points between the real samples were calculated by using linear interpolation as shown in Fig. 4. The linear interpolation method was applied to both model and the raw PMT pulses so that there would be minimal change in our program.

1.4 Median filtered zero crossing method

In this method, eight digital samples were selected at the rising part of the PMT signal based on the selection of a threshold value. It is worth to note that the number of the selected digital samples was one of the four variables depending on the sampling rate. A total of five points were picked around each digital sample and the time mark was calculated based on a simple linear fit and five selected points around Point 8. After the time marks were sorted by their values, the median value was used as the time mark of an event. Similarly, the second time mark was determined and the time difference was calculated.

In this method, the initial number of the selected points, the number of points used in the linear fit and the threshold value were optimized for the best timing response.

2 Experiment setup

A diagram of the coincidence detection components configuration and signal flow is illustrated in Fig. 5.

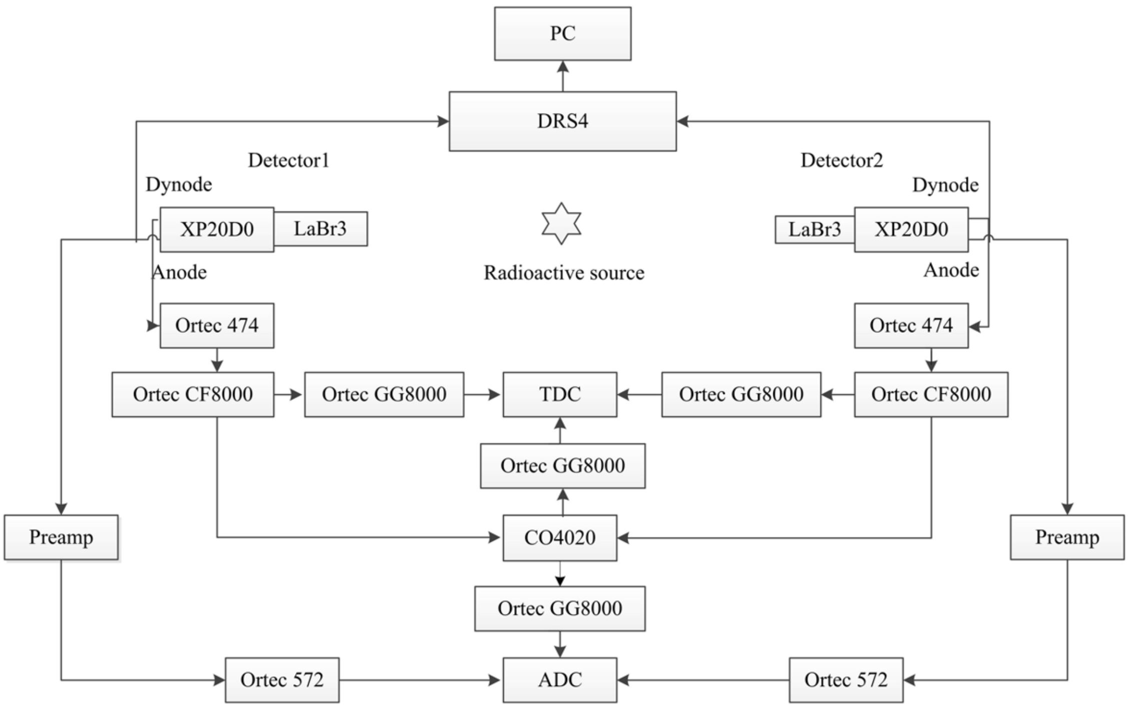

Fig. 5 (color online) Schematic set-up used to measure time and energy information in the analog system. The signal from PMT dynode also acquired by DRS4 digital system for further analysis.

Two ϕ20 mm × 0.5 mm $LaBr_3$ scintillators were instrumented with Photonis XP20D0, which had enhanced timing capability due to a screening grid at the anode and enhanced quantum efficiency of modern photocathodes, placed 30 cm apart with ^{22}Na source between them. The source was in an aluminum holder placed on an aluminum track of the source holder. The holder was initially placed 5 cm from the left-most detector and a data set was collected. The source was then moved 10 cm to the right and another data set collected. This was repeated until the source was moved a total of 20 cm. The expected difference in arrival time (δt) of the detector pulse is $\delta t = 2d/c$, where c is the speed of light and d is the distance the source is moved. By moving the source a total of 20 cm, it is expected that the difference between the arrival times at the two extremes will shift 1.33 ns, or one time step of ADC.

One output was connected to an analog system that was used both as a coincidence trigger for the analog-to-digital converter (ADC) as well as to determine the difference in pulse arrival time.

The analog-time equipment included an Ortec model CF800 (CFD), Phillips 7186 time-to-digital converter (TDC), and a multi-channel analyzer (MCA). The delay time of signal after the CFD was 2 ns.

The DRS4 simultaneously digitized two waveform at 5 GS/s each and collected 1 024 samples before trigger. Both digitized waveforms were saved to computer hard drive and post processed with various digital analysis routines to determine the difference of their times. Two-hundred-thousand waveforms were captured and saved for post-processing at each source location.

Two pulses digitized by the ADC from the fan-out are graphed in Fig. 6. The energy resolutions at 511 keV are measured to be 4.2% and 5.8% (FWHM) for two detectors, respectively .

The higher energy region of the spectrum is better than the lower energy part, which may be caused by the high statistics in that region. The first peak in low part of energy spectrum is the backscatter peak, while the second one is the Compton edge.

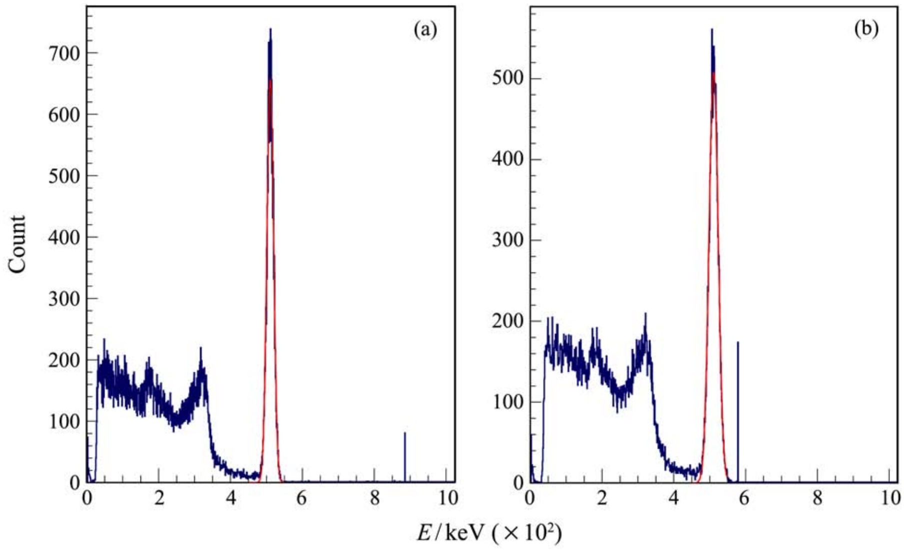

Fig. 6 (color online) Example of pulse height distributions digitized by ADC: (a) detector1, (b) detector2. The conditions were: Photonis XP20D0; ϕ20 mm × 0.5 mm $LaBr_3$ scintillators; ^{22}Na radioactive source. The energy resolutions are less than 6% (FWHM).

3 Results and discussion

3.1 Energy spectrum

To obtain the energy of the event, the area of the waveform is integrated for 150 ns from the pulse start. The photon-peak of the spectrum is normalized to 511 keV. The photon-peak is clearly separated from the Compton scattering, and the energy resolutions at 511 keV are measured to be 3.2% and 4.2% (FWHM), respectively for two detectors. The energy resolutions digitized by DRS4 evaluation board and ADC are listed in Table 1, it can be seen that the different between the analog and digital is small.

Table 1 Energy resolutions of two Detectors digitized by ADC and DRS4 evaluation board, respectively.

Method	Energy Resolution (Detector1)/%	Energy Resolution (Detector2)/%
ADC	4.2	5.8
DRS4	3.2	4.2

3.2 Time resolution

The coincidence time between the XP20D0 PMTs is measured for events in the photo-peak; the energy of the XP20D0 is obtained, and photo-peak event with [400, 650] keV energy for both PMTs are selected for the coincidence measurement.

The example of time difference between two detectors is shown in Fig. 7.

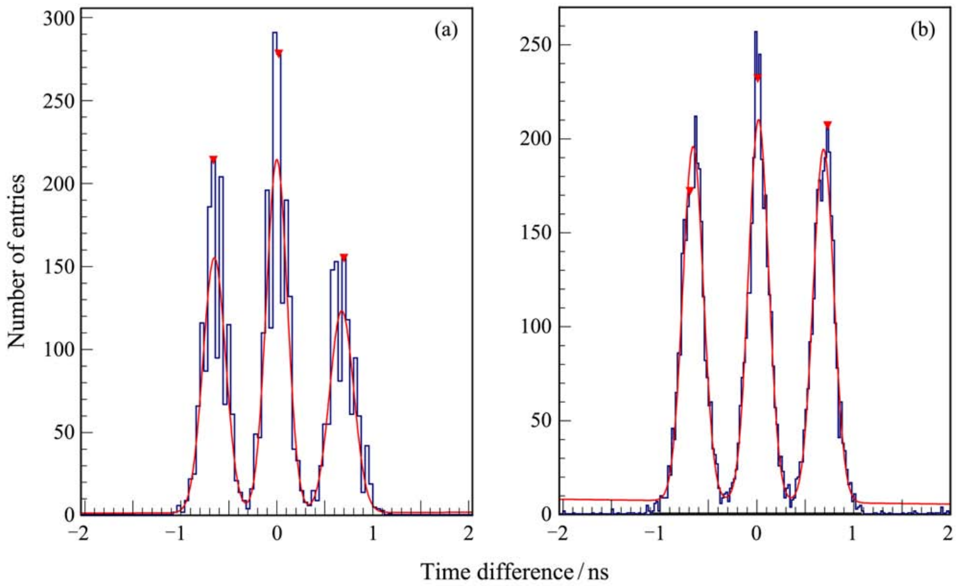

Fig. 7 (color online) Distributions of the T_1-T_2 time difference: (a) TDC, (b) DRS4. ^{22}Na radioactive source was moved from the left-most side to the right-most side, and three data sets were collected.

The best resolution and most accurate results are summarized in Table 2. Although the median filtered method are easy to implement, these methods had a resolution on the order of the sampling time, which were the least accurate of the methods analyzed.

The ability to implement a true CFD in the digital regimes does not improve the resolution (247.1 ps) or the accuracy of using the analog equipment with average time resolution of 254.7 ps. The Gaussian fit yielded good resolution, however, is much more time consuming. The results from these two methods are essentially equal in both resolution .

Mean PMT pulse model results in the best accuracy and precision, with average time resolution of 195.4 ps.

Table 2 Summary of the methods and the best time resolution used in this study.

Method	Time Resolution/ps
CFD zero-crossing	247.1
Pulse-shape fitting	250.7
Mean PMT pulse model	195.4
Median filtered method	309.7

4 Conclusions

This paper examined the ability of different timing method to interpolate the arrival time of a digitized radiation detector signal. It was found that the best method was also the most time consuming. There is also a different in resolution and accuracy. While some methods show good resolution, the accuracy of the results may vary.

This paper demonstrated that digital signal processing can approach resolutions of less than 200 ps and the ability of interpolating the arrival time of digital signals between digital time steps can approach the determination of the arrival time of the signals in the analog regime.

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基于DRS4测试板的数字波形分析方法

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摘要： 使用不同的方法来确定$LaBr_3$晶体信号的到达时间。在文中信号经过光电倍增管的放大之后由DSR4测试板进行数字采集，其中DRS4是由瑞士PSI研究所生产的高带宽、低功耗以及快读出时间的开关电容阵列。这些优势使得DRS4很具有吸引力，很多实验将传统的ADC与TDC替换为DRS4。采集的波形可以通过不同的方法进行后续处理。其中包括: (1) 恒分甄别、(2) 波形拟合、(3) PMT脉冲模型法以及(4) 均值过滤法。文中实现的恒分甄别的时间分辨与使用模拟电路获取的平均时间分辨相比没有提高。高斯波形拟合法虽然与数字CFD的结果相当，但是却更加耗时。均值滤波法虽然容易实现，但是通过这个方法得到的时间分辨与采样时间在一个量级。而PMT脉冲模型法得到的平均时间分辨为195.4 ps，优于模拟信号的恒分甄别的时间分辨254.7 ps。

关键词： $LaBr_3$; DSR4; 时间分辨

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