

Precision timing measurement of phototube pulses using a flash analog-to-digital converter

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Abstract

We present the timing characteristics of the flash ADC readout of the GlueX forward calorimeter, which depends on precise measurement of arrival time of pulses from FEU 84-3 photomultiplier tubes to suppress backgrounds. The tests presented were performed using two different 250 MHz prototype flash ADC devices, one with eight-bit and one with twelve-bit sampling depth. All measured time resolutions were better than 1 ns, independent of signal size, which is the design goal for the GlueX forward calorimeter. For pulses with an amplitude of 100 mV the timing resolution is 0.57 ± 0.18 ns, while for 500 mV pulses it is 0.24 ± 0.08 ns.

Keywords: flash ADC, calorimeter, time resolution, PMT pulse

1. Introduction

The forward electromagnetic calorimeter (FCAL) of the GlueX experiment [1] at Jefferson Lab will use flash analog-to-digital converters (FADC) to detect signals from final-state photons, produced in photon-nucleon reactions. The calorimeter will consist of 2800 $4 \text{ cm} \times 4 \text{ cm} \times 45 \text{ cm}$ type F8 lead glass blocks, each coupled to an FEU 84-3 photomultiplier tube (PMT). Electrons and positrons produced in the electromagnetic shower from an incident photon generate Cherenkov radiation that will be converted to a current pulse by the PMT. The PMT pulses will be digitized by twelve-bit 250 MHz multi-channel FADC boards [2]. Continuous digitization by the FADC preserves the signal pulse shape, enabling simultaneous measurement of total charge, which is the integral of the pulse, and signal arrival time. The integrated charge is proportional to the energy that the incident particle deposited in the block and the pulse shape can be used to determine the arrival time of the particle.

The pulse arrival time will be used to (1) isolate final-state photons from out-of-time hits in the detector that result from the expected high level of electromagnetic background and (2) determine the exact beam bunch that produced the collision of interest. The electromagnetic background arises from the photon beam, which will be delivered at an average rate of $10^8 \text{ } \gamma/\text{s}$ incident on the target (at energies of approximately 9 GeV) with beam bunch spacing of 2 ns. Predicted background rates on the FCAL modules closest to the beam axis are of order 1 MHz; elsewhere in the detector the background rate is at the order

of 10 kHz. Given the bunch spacing, a timing resolution of better than 1 ns for each FCAL block is desired to both suppress electromagnetic background and perform bunch identification. Note that a typical event will illuminate multiple blocks, thereby providing numerous independent measurements of the event time, each with better than 1 ns resolution, which will allow a determination of the beam bunch that produced the event of interest.

In order to make optimal use of the data bandwidth available, it is critical that the timing measurement of the pulses be done in real-time as part of the digital signal processing of the FADC buffer for each event. We will present two such processing algorithms to determine the timing information from a PMT signal, both of which utilize samples from the leading edge of the PMT pulse. We demonstrate that both of these algorithms provide time resolution sufficient for the needs of the GlueX experiment.

2. Hardware characteristics

The readout of the GlueX forward calorimeter will consist of 2800 Russian-made FEU 84-3 PMTs, each powered by a 24 V Cockroft-Walton base [3]. The PMTs will be connected to multiple 16-channel 250 MHz twelve-bit FADC boards, designed and produced by Jefferson Lab [2]. For tests described in this article, we utilized a single-channel eight-bit 250 MHz FADC developed at Indiana University in addition to a prototype eight-channel twelve-bit 250 MHz FADC developed by Jefferson Lab. We will briefly describe these two FADC devices and the pulse shape of the FEU 84-3 phototube below.

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2.1. Single- and multi-channel FADC

The eight-bit single-channel FADC prototype has been implemented as a PCI card so that it can be tested using a standard personal computer. The FADC digitizer samples the input signal at 4 ns intervals, and the samples are continuously written into a dual-port ring-buffer. This enables the extraction of the samples without interrupting the digitizer. The data are read out over the PCI bus. The three processes, digitization, extraction and read out, are independent of each other and can happen simultaneously, which allows the device to have zero dead-time. The analog input saturates for voltages above ≈ 1.15 V.

The twelve-bit 250 MHz FADC is based on the MAX1215 chip with a 1.45 V dynamic range. Like the eight-bit board, this device is also a zero dead-time device. It has the ability to read signals simultaneously from up to eight PMTs, with the digitization of all channels synchronized to the same clock. The board is based on the VME64x platform. More details on the operation and characteristics can be found in Ref. [2].

2.2. Characteristics of the FEU 84-3 PMT pulse

Figure 1 shows a typical pulse from a FEU 84-3 PMT obtained by digitizing the signal every 0.2 ns with a digital oscilloscope. The line in Fig. 1 represents the fit obtained using a sum of a bifurcated Gaussian and a constant B ,

$$S(t) = A \exp \left[-\frac{(t - t_p)^2}{2\sigma_k^2} \right] + B; \quad k = \begin{cases} 1 & t < t_p \\ 2 & t \geq t_p \end{cases}, \quad (1)$$

where A represents the amplitude of the signal, t_p is the peak arrival time and $\sigma_{1,2}$ are the Gaussian widths that model the duration of the rising and falling edges, respectively. It is evident that the rising edge is well reproduced by a Gaussian line-shape, and this feature will be employed by one algorithm for the online extraction of the pulse arrival time. In addition, pulse characteristics are given by the parameters of the bifurcated Gaussian fit. We found that the characteristic leading-edge time (σ_1) is about 9 ns independent of the pulse amplitude.

Since the pulse varies slowly around the peak, the peak sample time is a poor choice to characterize the arrival time of the pulse. We choose a characteristic signal time corresponding to the time at which the pulse has reached half of the signal maximum. We call this time t_0 and discuss below two algorithms to measure t_0 .

3. Timing algorithms

We explored two methods to obtain the characteristic time of a pulse that both rely on two FADC samples on the rising edge of the pulse. Other methods have been used, *e.g.*, using the first algebraic moment [4]; however, we have had obtained the most precise results using the methods outlined below. In the discussion that follows we assume that all FADC measurements have been adjusted to remove the portion of the signal due to the DC offset, *i.e.*, all FADC samples are “pedestal subtracted.”

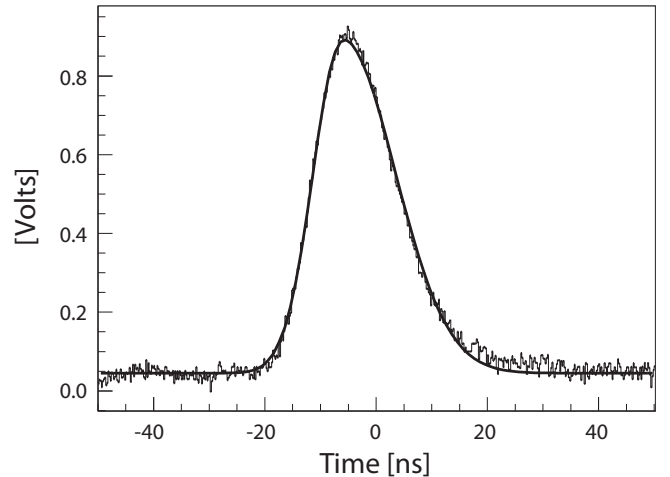


Figure 1: A typical pulse from FEU 84-3 PMT obtained from a digital oscilloscope. (The pulse has been inverted for comparison with FADC data.) The solid line represents a fit to a bifurcated Gaussian with a constant offset.

3.1. Gaussian transformation

This method takes advantage of the fact that the rising edge of the pulse from the PMT is Gaussian in shape. Initially proposed by Teige *et al.* [5] it is based on the transformation that turns a Gaussian edge into a straight line:

$$S'_i = \sqrt{-\ln \left(\frac{S_i}{S_p} \right)}, \quad (2)$$

where S_p is the peak sample, while S'_i is the transformed sample obtained from an original sample S_i at the time t_i .

The transformed rising edge samples are now a linear function of time

$$S'_i = a_G t_i + b_G. \quad (3)$$

with the slope, a_G , and the intercept, b_G , related to the parameters of the rising-edge Gaussian, Eq. 1. The parameters of the straight line can be calculated using any two samples from the rising edge. The line, in turn, determines the time when the pulse reached any given fraction of its peak value. In particular, t_0 is given by

$$t_0 = \frac{\sqrt{-\ln \left(\frac{1}{2} \right)} - b_G}{a_G}, \quad (4)$$

It was found that the two samples immediately preceding the peak sample give the best measure of t_0 in this approach [5].

3.2. Linear interpolation

It was desirable to test a different algorithm which did not involve mathematical operations such as a square-root and a logarithm in order to facilitate adaptation of the algorithm to the FADC field-programmable gate-array

139 (FPGA). For that reason we considered another method
 140 that assumes that the rising edge is a linear function of
 141 time in the vicinity of t_0 . A similar technique has been
 142 utilized with success by the VERITAS Collaboration [6].
 143 This assumption allows one to define the line by one sam-
 144 ple preceding and the other one following half of the peak
 145 sample S_p . These samples are labeled S_- and S_+ respec-
 146 tively. In this approach, the slope and intercept are given
 147 by

$$a_L = \frac{S_+ - S_-}{T} \quad (5)$$

$$b_L = S_+ - a_L t_+, \quad (6)$$

148 respectively, where the time t_+ corresponds to the time of
 149 sample S_+ and T is the sampling period, which is 4 ns for
 150 the two FADCs we studied. The characteristic time is now
 151 determined by

$$t_0 = \frac{S_p/2 - b_L}{a_L}. \quad (7)$$

153 In both approaches, we desire an algorithm that will
 154 provide a stable measurement of the characteristic pulse
 155 time independent of the pulse amplitude and other ran-
 156 dom variations in the pulse shape. In all cases the timing
 157 information will be used comparatively, that is, we are
 158 interested in comparing the characteristic time of some
 159 channel to another channel in the detector array. There-
 160 fore, *constant*, systematic offsets of t_0 from the true time
 161 at which the signal reaches half maximum are irrelevant.

162 4. Timing resolution measurements

163 We tested the performance of the timing algorithms
 164 using an eight-bit single-channel and a twelve-bit multi-
 165 channel FADC. With the single-channel FADC we exam-
 166 ined digitization effects on the time resolution by effec-
 167 tively digitizing the same pulse twice with the FADC. Such
 168 an approach removes statistical variations in pulse shape
 169 and explores the true resolution of the algorithm. Using
 170 the multi-channel FADC we were able to recreate an envi-
 171 ronment comparable to that which we expect in the final
 172 detector. By examining channel-to-channel differences in
 173 the algorithm-determined characteristic time of a common
 174 light source we were able to measure final timing resolu-
 175 tions for individual channels and explore the dependence
 176 of these resolutions on pulse amplitude.

177 4.1. Measurements with single-channel FADC

178 A single-channel eight-bit prototype was used to mea-
 179 sure the timing resolution of the algorithms mentioned
 180 above. The light source in use was a small piece of scintil-
 181 lator, illuminated by a nitrogen laser LN300C. The light
 182 from the scintillator was propagated via optical fiber into
 183 a dark-box containing an FEU 84-3 and an XP-2020 pho-
 184 totube. The operating voltage for FEU 84-3 was set at

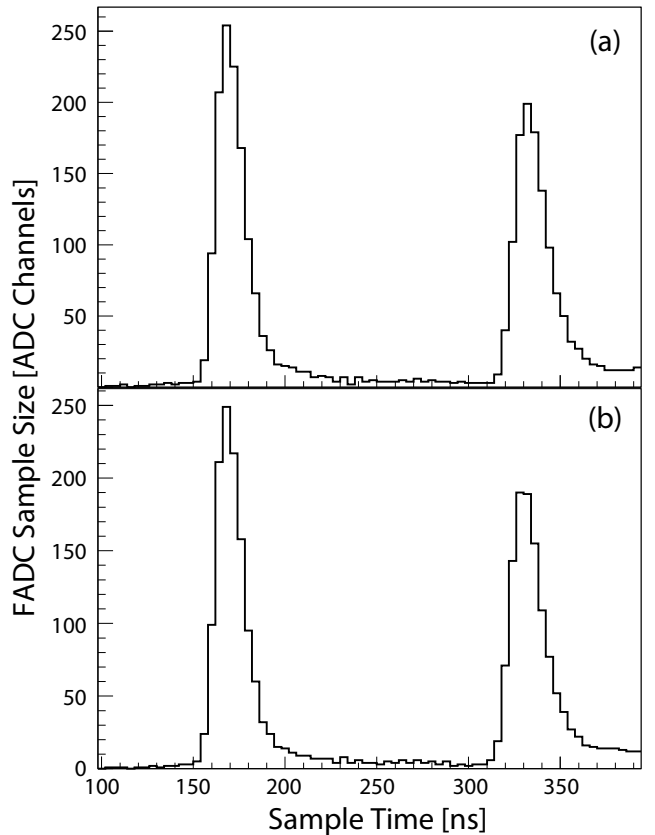


Figure 2: Typical FADC response for the primary and reflected pulse for two different delays. Comparing the reflected pulse between panel (a) and (b) demonstrates what is termed in the text a difference in “sampling phase.”

about 1600 V, and the fast XP-2020 PMT was used as a trigger.

We devised a simple setup where the signal from a FEU 84-3 PMT was split, with one branch connected to the FADC and one end of the other branch left unterminated. The unterminated end produced a reflected pulse that was delayed, but still digitized within the same FADC buffer as the primary pulse. If one neglects distortion and attenuation introduced by the delay cable, this technique produces two identical pulses with fixed separation in time and removes contributions to the resolution from fluctuations in shape or transit time in the PMT. As long as the pulses are well separated in time, the algorithms described in Sec. 3 can be applied to obtain the difference in characteristic time of two pulses Δt_0 . Since the true delay is fixed, the standard deviation of Δt_0 provides the quadrature-sum of the resolutions with which the characteristic times of the two pulses are determined.

Figure 2 shows typical FADC responses for two different lengths of the open-end cable. Comparing the reflected pulse between panels (a) and (b) of Figure 2 demonstrates what we term a difference in “sampling phase.” One can see that with Figure 2(b) the delay of the second pulse is

such that the peak is likely to fluctuate between two adjacent samples, with the true peak being in the middle and slightly higher than the two. As both algorithms depend on obtaining a sample at the peak, one anticipates some added uncertainty when the primary and reflected pulses are sampled with different phases. By changing the length of the open end, one can control the delay between two pulses, modifying the probability that the sampling phase is different between the primary and reflected pulses, and explore the sensitivity of the timing resolution to the relative alignment of the samples with the structure of the pulse. It is important to note that there is no synchronization between the FADC clock and the laser or trigger hardware, so it is impossible to control the absolute phase with which the pulses are sampled.

The dependence of the time resolution on length of the delay cable can be seen in Fig. 3, where, for various delays of the reflected pulse, we plot the standard deviation of Δt_0 , $\sigma(\Delta t_0)$, obtained by applying the Gaussian (filled circles) and linear-interpolation (open circles) methods. The x -axis represents the mean of Δt_0 modulo 4 ns. The best time resolution is obtained with a signal delay such that the peak region of both pulses are sampled with the same phase (as shown in Fig. 2(a)). Naively, one would expect this to occur only when the delay cable length is a multiple of 4 ns; however, bifurcated gaussian fits to both the primary and reflected pulse indicate that the characteristic rise time, σ_1 in Eq. 1, of the reflected pulse is approximately 0.5 ns larger than the first due to dispersion in extra length of cable. This shifts the minimum of $\sigma(\Delta t_0)$ from 4.0 ns (or 0.0 ns) to about 3.5 ns. The worst resolution from both methods occurs when the delay is changed by approximately 2 ns with respect to this minimum, corresponding to the case where both pulses are sampled with maximally different phases in the peak region (as shown in Fig. 2(b)). In this case, the resolution in time-difference is larger for the linear-interpolation method by about 70 ps.

Assuming that $\sigma(\Delta t_0)$ arises from equal contributions of the timing resolution of the primary and reflected peak, we can estimate the time resolution for the algorithm itself varies from 50 (40) to 110 (150) ps for the the Gaussian (linear-interpolation) methods.

4.2. Measurements with multi-channel FADC

Pulse-to-pulse and channel-to-channel variations in transit time through the PMT and shape of the pulse will introduce fluctuations in the measured t_0 – we call these fluctuations the “statistical” contribution to the resolution as they arise from random effects. We expect also an additional “systematic” shift in the measured t_0 as a function of pulse height. This systematic shift must be corrected in order to compare t_0 between two blocks in the array with different amounts of energy deposition. The studies presented in the previous section only explore the resolution of the algorithm itself, hence a different approach is needed to examine these additional contributions to the timing resolution.

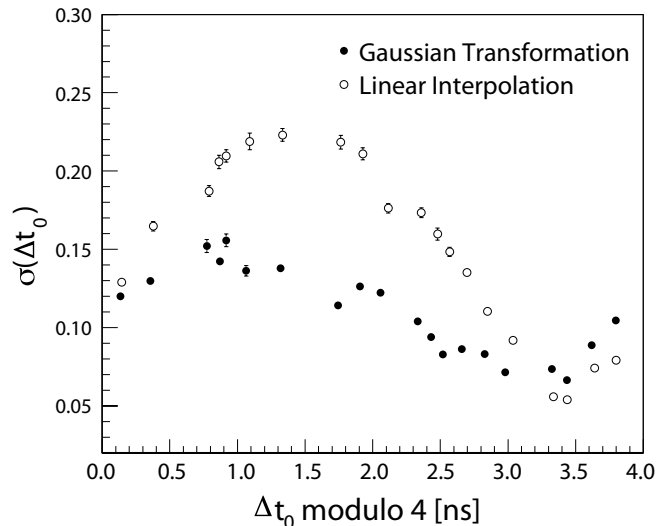


Figure 3: The value of $\sigma(\Delta t_0)$ as a function of the mean delay (Δt_0) modulo 4 ns obtained by applying Gaussian (filled circles) and linear-interpolation (open circles) methods. The errors are statistical only.

To better mimic the final detector configuration, we constructed an array of nine lead glass blocks optically coupled to PMTs which were powered by Cockcroft-Walton bases. All of the blocks in the array were simultaneously illuminated by a pulsed LED, which was mounted in front of a diffusion panel oriented about 30 cm from the face of the lead glass array. The LED was driven by a pulsing circuit with a pulse rate of about 1 kHz. A capacitive circuit was used to shorten the duration of the applied electrical pulse to the LED to less than 5 ns. The entire setup was enclosed in a light tight box. One of the blocks in the experimental array was used as a trigger for the data acquisition system, while the remaining eight were connected to the FADC for data collection.

Our goal was to extract the statistical and systematic contributions to the resolution as a function of pulse amplitude. To reduce the pulse size, the incident light was attenuated. In order to have a set of control data with which to compare those blocks with varying pulse amplitudes, a screen was placed in front of only four blocks with the other four uncovered. The amplitude was varied by placing successively more screens in front of the appropriate blocks. The procedure was repeated using two different sets of control blocks. In order maintain a relatively constant transit time through the PMT throughout the study, the bias voltage on the PMTs remained constant at the values in Tab. 1, which roughly equalized the gains for all PMTs. (In the normal operating range of the FEU 84-3 PMT, variation in the bias voltage changes the transit time through the PMT by approximately 1 ns per 100 V change in bias voltage.)

As shown in Fig. 4, the difference in t_0 for any two channels i and j for a set of events can be characterized by a Gaussian distribution with mean $\Delta t_{0,ij}$ and stan-

Table 1: PMT cathode voltage and pulse amplitude for various array elements. The typical amplitude of the pulses was about 500 mV when no light-attenuating screens were installed.

Channel	Voltage [kV]	Amplitude [Channels]
1	-1.495	1376
2	-1.545	1398
3	-1.610	1414
4	-1.585	1405
5	-1.455	1374
6	-1.500	1401
7	-1.555	1371
8	-1.515	1439

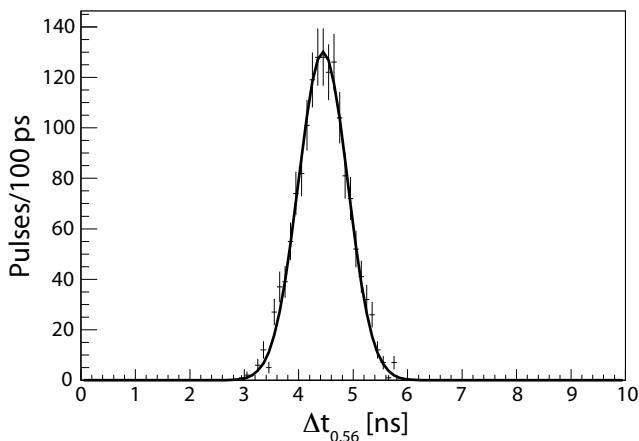


Figure 4: This histogram of the difference in t_0 in two channels shows that the distribution is essentially Gaussian in shape. Note that the two pulses do not arrive at exactly the same time.

standard deviation σ_{ij} . To obtain the mean value of the signal arrival time $t_{0,i}$ and statistical contribution to the resolution σ_i for a single channel, a simple set of equations was used. For n independent channels there are, in principle, $n(n-1)/2$ unique, non-trivial equations of the form

$$\Delta t_{0,ij} = t_{0,i} - t_{0,j} \quad (8)$$

$$\sigma_{ij} = \sqrt{\sigma_i^2 + \sigma_j^2}. \quad (9)$$

For a given configuration of the array, each pulse is digitized by the FADC and processed using the timing algorithms described in Sec. 3. The differences in t_0 for successive channels are fit to a Gaussian shape, from which $\Delta t_{0,ij}$ and σ_{ij} are extracted. Collections of these fitted values are then utilized to study statistical fluctuations and systematic shifts in t_0 as a function of pulse height, as discussed below.

In order to obtain an accurate value of the statistical contribution to the resolution of a single channel as a function of signal size, we first determine the resolutions for the four control channels by using a χ^2 fit. For these four channels there are six independent values σ_{ij} . It is possible to

Table 2: Extracted t_0 standard deviations for the Gaussian transformation method (σ_G) and the linear interpolation method (σ_L) at pulse amplitudes of about 500 mV. These measurements represent the dominant, statistical contribution to the resolution.

Channel	σ_G [ns]	σ_L [ns]
1	0.28 ± 0.01	0.25 ± 0.01
2	0.31 ± 0.01	0.28 ± 0.01
3	0.29 ± 0.01	0.25 ± 0.01
4	0.30 ± 0.01	0.28 ± 0.01
5	0.27 ± 0.01	0.26 ± 0.01
6	0.30 ± 0.01	0.28 ± 0.01
7	0.27 ± 0.01	0.26 ± 0.01
8	0.29 ± 0.01	0.28 ± 0.01

choose a set of four σ_i that minimizes a function given by

$$\chi^2 = \sum_{i=1}^4 \sum_{j=i+1}^4 \left(\frac{\sigma_{ij} - \sqrt{\sigma_i^2 + \sigma_j^2}}{\delta(\sigma_{ij})} \right)^2, \quad (10)$$

where $\delta(\sigma_{ij})$ is the error in σ_{ij} obtained from the Gaussian fit to the time-difference distribution. The minimization of this function yields values for the statistical contribution to the resolution. Repeating for the other set of four channels gives resolutions for all eight blocks in the array (at pulse amplitudes of about 500 mV) as shown in Tab. 2.

Assuming the resolutions of the four control blocks are constant, the values of σ_i for the four blocks with attenuated light input may be calculated using Eq. 9. The experiment is then repeated again with a different choice of control channels, allowing us to study all eight channels in the array. The process is repeated while varying quantity of light incident on the channels under study in order to map out the dependence of the statistical contribution to the resolutions as a function of pulse amplitude. The dependence is shown for the best and worst resolution channels in Fig 5 for the Gaussian transformation and linear interpolation method. For relatively low pulse amplitudes the resolution is still better than 1 ns and appears to be in the range of 200-400 ps for larger pulses.

The calculation of statistical contribution to the resolutions depends upon the choice of control channel used to determine σ_{ij} . Any one channel may be compared to four different control channels. As a cross check on our procedure we varied the control channel used in our extraction of the statistical contributions to the resolution. This variation produced changes in measured σ_i of less than 40 ps over the entire range of pulse amplitudes indicating that our procedure is robust.

The statistical contributions to the resolution were fit to

$$\sigma(S_p) = \frac{a}{S_p} + b, \quad (11)$$

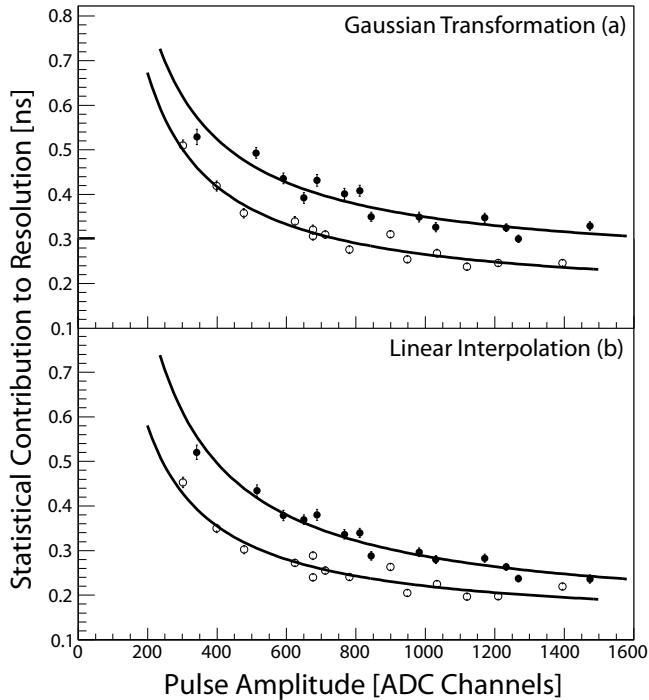


Figure 5: The statistical contribution to the timing resolution of channels 1 (open circles) and 8 (filled circles) are plotted as a function of pulse amplitude for the Gaussian transformation (a) and linear interpolation (b) timing algorithms. These two channels represent the highest and lowest resolution of all elements in the array – measurements for the other six channels are between these extremes.

where a and b are free parameters (as shown in Figure 5). The average value for a over all eight channels was determined to be 117 ± 34 (114 ± 46) channels-ns while that for b is 0.203 ± 0.079 (0.155 ± 0.077) ns for the Gaussian transformation (linear interpolation) algorithm. At an amplitude of 500 mV the average statistical contribution to the resolution is 0.29 ± 0.09 (0.24 ± 0.08) ns, while at an amplitude of 100 mV the resolution is 0.62 ± 0.16 (0.56 ± 0.18) ns for the Gaussian transformation (linear interpolation) method. The uncertainties of the results are derived from the standard deviation of the resolutions for all eight channels studied. Both algorithms provide comparable resolution.

The values of the average pulse arrival time $t_{0,i}$ calculated from the same data sets are shown in filled squares in Fig. 6. These data show a significant systematic shift in $t_{0,i}$ as a function of pulse amplitude. In order to account for this shift, which would otherwise cause instability in the measurement of t_0 under variations of the pulse amplitude, the values of t_0 for each channel were corrected by the procedure

$$t_{0,i} \rightarrow t_{0,i} + \alpha S_p, \quad (12)$$

where α is a single parameter, apparently characteristic of the algorithm and FEU 84-3 pulse shape. In this study, α was calculated to be about -7×10^{-4} ns/ADC counts, independent of channel and also digitization algorithm. This

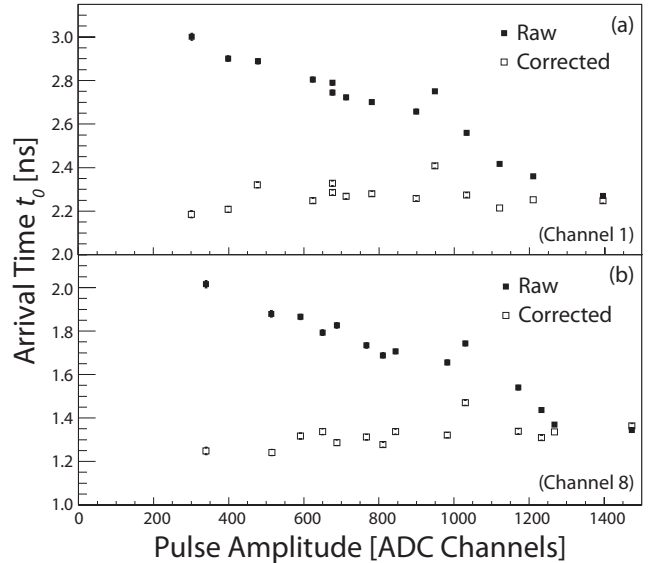


Figure 6: The uncorrected t_0 values (filled squares) as a function of signal amplitude calculated from the linear interpolation method for channels 1 (a) and 8 (b). The values after the correction given by Eq. 12 are shown as open squares. Other channels are consistent with these, and similar behavior is observed for the Gaussian transformation algorithm.

correction, which is applied to the measured characteristic time, dramatically reduces the dependence of the characteristic time on pulse amplitude as shown in Fig. 6 and, consequently, reduces the systematic contribution to the timing resolution.

The total contribution to the timing resolution from statistical and residual systematic fluctuations can be characterized as

$$\sigma(S_p) = \sqrt{\left(\frac{a}{S_p} + b\right)^2 + c^2}, \quad (13)$$

where a and b are determined as discussed above and c is the error due to the residual systematic contribution to the resolution. By computing the standard deviation of the corrected t_0 for all channels over a range of pulse amplitudes (as is shown for two channels in Fig. 6) the value for c was determined to be 0.05 ns, a minor contribution when added in quadrature of the statistical contributions given by a and b .

5. Conclusions and discussion

We have presented two signal processing algorithms for converting flash ADC data into a measurement of the arrival time of an FEU 84-3 PMT pulse. One algorithm utilizes the fact that the leading edge of the pulse can be described by a Gaussian, while the other uses a linear approximation to the leading edge in the vicinity of the time at which the pulse has reached half of its maximum

403 amplitude. We have measured the resolution of these algo-460
404 rithms and also the anticipated resolution with which we461
405 can measure a characteristic arrival time of a PMT pulse462
406 in the final GlueX detector configuration. 463

407 By devising a technique to delay and digitize the same464
408 pulse twice with a single-channel eight-bit FADC we stud-465
409 ied the capabilities of the timing algorithms, independent466
410 of variations in pulse shape or transit time through the467
411 PMT. At a pulse height around 1.0 V, corresponding to468
412 roughly 85% of the full scale of an eight-bit FADC, we469
413 determine that timing resolution of the Gaussian transfor-470
414 mation algorithm is in the range of 50-110 ps, while the res-471
415 olution for the linear interpolation algorithm is 40-150 ps.472
416 The variation in resolutions is attributable to variations473
417 between the true time of the signal peak and the phase
418 of the sampling clock. The time resolution that can be
419 obtained by applying the two methods is only a fraction 474
420 of the 4 ns time between samples. 475

421 The relevant timing resolution for a single channel in476
422 the GlueX calorimeter includes contributions from the tim-477
423 ing algorithm, statistical contributions from pulse-to-pulse478
424 variations in shape and PMT transit time, and systemat-479
425 ic contributions arising from dependence of measured480
426 arrival time on pulse height. A nine-channel array was481
427 constructed to study these effects. The statistical fluct-482
428 uations in arrival time, which depend on pulse ampli-483
429 tude, dominate the timing resolution and were measured484
430 as a function of pulse amplitude for both algorithms. The485
431 systematic shift in measured time as a function of pulse486
432 amplitude appears to be linear and consistent across all487
433 channels for both of the timing algorithms. This allows488
434 for a simple, single-parameter correction to be performed,489
435 which reduces the systematic contribution to the timing490
436 resolution to about 50 ps, making it nearly negligible.491
437 The linear interpolation algorithm performs slightly better492
438 than the Gaussian interpolation algorithm, although ei-493
439 ther would meet the resolution demands of the GlueX for-494
440 ward calorimeter. Assuming the use of the linear interpola-495
441 tion algorithm, the estimated final timing resolution antic-496
442 ipated in the detector for FEU 84-3 PMT pulses with am-497
443 plitudes of 100 mV (500 mV) is 0.57 ± 0.18 (0.24 ± 0.08) ns,
444 where the central values include the quadrature-sum of
445 statistical and systematic contributions to the resolution.

446 Since the algorithms rely on sampling the pulse on its
447 leading edge and near the peak, we anticipate that mea-
448 surements of the characteristic pulse time will remain ro-
449 bust in a high rate environment assuming PMT pulses
450 do not overlap. The digital signal processing electronics
451 could further be modified to apply the algorithm to mul-
452 tiple detected peaks in a single flash ADC buffer. The full
453 FEU 84-3 pulse fits inside of a 40 ns window. The 1-2%
454 of FCAL modules that are closest to the beam axis have
455 expected background rates of > 1 MHz. For the highest
456 rate modules the probability of pulse overlap may reach
457 10%, resulting in some small background contamination.
458 For the remaining 98% of the modules, the probability of
459 overlap is expected to be negligible.

Both algorithms presented provide comparable timing
resolution that is suitable for our application. The differ-
ence in the two algorithms is in the implementation. The
Gaussian transformation algorithm relies on more compli-
cated mathematical functions; however, has the advantage
that it always uses the peak sample and the two samples
immediately preceding the peak. The linear interpolation
algorithm, while mathematically more simple, requires a
search and comparison of all samples on the leading edge
to find the sample immediately before and after the point
at which the signal level crosses half the maximum value.
The exact choice of algorithm for the GlueX application
will depend on which technique can be most efficiently im-
plemented in flash ADC FPGA.

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- [1] See, for example: M. R. Shepherd, *Proceedings of the Tenth Conference on the Intersection of Particle and Nuclear Physics*, AIP Conf. Proc. 1182, 816 (2009); <http://www.gluex.org>.
- [2] F. J. Barbosa *et al.*, IEEE Nuclear Science Symposium, Hawaii, USA (2007).
- [3] A. Brunner *et al.*, Nucl. Instrum. Meth. **A 414**, 466 (1998).
- [4] J. Albert *et al.* Nucl. Instrum. Meth. **A 594**, 407 (2008); H. Von Der Schmitt *et al.*, Nucl. Instrum. Meth. **A 263**, 206 (1988).
- [5] S. Teige *et al.*, Internal memo, GlueX-doc 426 (2005).
- [6] P. Cogan, *Proceedings of the 30th International Cosmic Ray Conference*, arXiv:0709.4208 [astro-ph] (2007).