CLAS12 CTOF Time-Walk Corrections

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1 Overview

For the readout of scintillation counters, time walk is an instrumental shift in the measured TDC hit time that arises when using leading edge discriminators (LEDs). This shift in timing arises due to the finite rise time of the PMT analog pulse. For a given event time, pulses of different amplitude cross the discriminator threshold at slightly different times. The size of the effect therefore depends on the ADC pulse height. Fig. 1 shows an illustration of the timing shift due to time-walk effects associated with two events that cross a counter at a fixed time relative to the trigger but with different amplitudes.

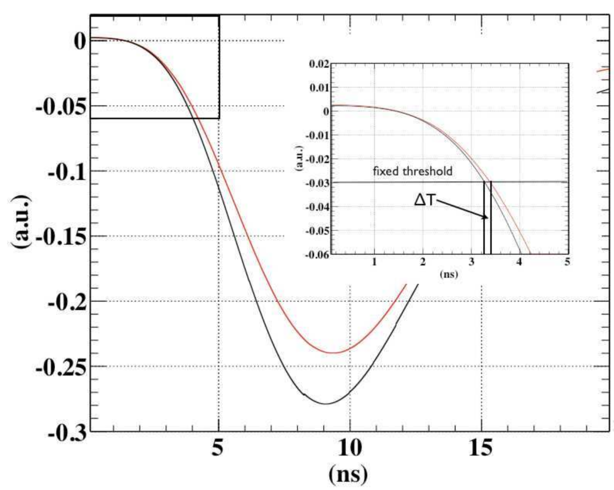

Figure 1: ADC pulse height (arbitrary units) vs. time relative to the trigger (ns) for two tracks crossing the counter at the same time but with different pulse heights to illustrate the time shift due to time-walk effects with a scheme employing readout with leading edge discriminators.

For the nominal CTOF readout in Hall B, the electronics include Ortec 935 quad constant fraction discriminators (CFDs). Several months of studies using CFDs have already been completed using cosmic rays in the CTOF assembly area test stand. These studies have allowed for a complete characterization of the counter response and an initial measurement of the counter timing resolutions. However, a subset of counters has been configured using LED readout. The purposes for these studies include:

- to understand the counter response without time-walk corrections
- to understand if LED readout with time-walk corrections can allow for comparable timing resolutions than the readout with CFDs
- to develop and test time-walk correction algorithms that will be used for the FTOF readout that employs LEDs.

Note that if LED readout is a viable alternative for the CTOF system, two full NIM bins of CFD modules that require individual front-panel connections to adjust and monitor all 98 channels could be replaced by only six VME LED modules whose channel settings can be set or readout remotely with simple control scripts.

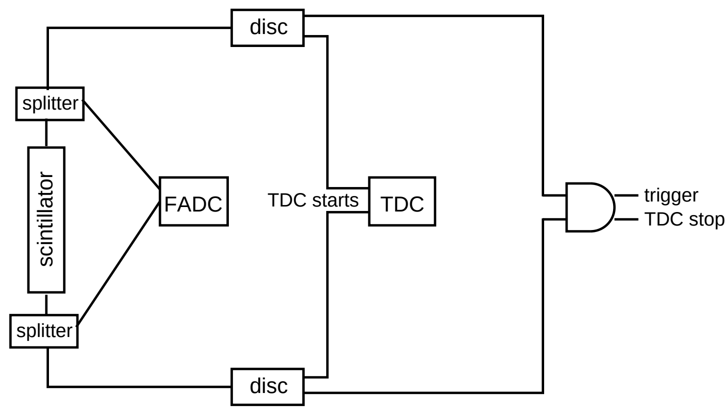

Figure 2: Electronics block diagram schematic for one CTOF counter.

2 CTOF Readout Configuration

In the CTOF cosmic ray test stand the detectors are placed into carts and aligned into vertical stacks. The 48 CTOF detectors are stored in 6 different carts each containing 8 counters. For the CTOF DAQ cosmic ray test stand each cart should be considered its own system independent of the others. The counters within each cart are as follows:

- Cart #1: Counters #1 → #8
- Cart #2: Counters #9 → #16
- Cart #3: Counters #17 → #24
- Cart #4: Counters #25 → #32
- Cart #5: Counters #33 → #40
- Cart #6: Counters #41 → #48

The basic electronics block diagram for each counter is shown in Fig. 2. Each PMT anode is connected to a signal splitter circuit. 90% of the signal goes to a discriminator which then is connected to a high resolution TDC (CAEN 1290a, 24 ps LSB resolution). 10% of the signal goes to the flash ADC (JLab 250 MHz FADC). The discriminators for carts #2 → #6 are Ortec 935 quad CFD modules. For cart #1, a JLab LED is employed for the readout of all counter PMTs.

The triggers for each cart are formed from neighboring triplets of counters. As an example, the trigger definition for cart #1 is given by:

$$\begin{aligned}\text{TRIGGER}_{\text{CART\#1}} &= (C1 \cdot C2 \cdot C3) + (C2 \cdot C3 \cdot C4) + (C3 \cdot C4 \cdot C5) \\ &\quad + (C4 \cdot C5 \cdot C6) + (C5 \cdot C6 \cdot C7) + (C6 \cdot C7 \cdot C8),\end{aligned}$$

where $Ci \equiv iU \cdot iD$ for $i = 1 \rightarrow 8$ is the AND of the upstream U and downstream D PMTs for each counter in the cart. The full trigger is the OR over all 6 carts and has a rate summed over all carts of ~3 - 4 Hz.

3 Time-Walk Algorithm

The basic unit of study for the time-walk corrections is a counter triplet, which is defined as a cosmic ray track that passes through three consecutive counters within a single cart. Fig. 3 shows a schematic illustration of a triplet.

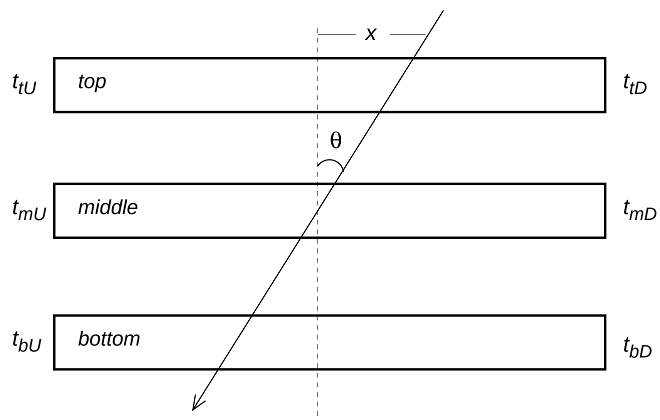

Figure 3: Schematic representation of a counter triplet made up of three identical scintillation counters. For the CTOF system, the scintillators have PMT readout at each end. The counters are labeled as top (t), middle (m), and bottom (b). The times t_i, $i = tU \rightarrow bD$, represent the measured PMT times relative to the trigger time.

The basic steps to determine and apply the time-walk corrections to the measured TDC times for the counters in cart #1 are described in the following subsections.

3.1 Timing Residual Definitions

Counters #2 to #7 are such that they can be the middle counter in a counter triplet. When they are the middle counters in a triplet, we can define the time residuals Δt for the middle upstream U and downstream D PMTs as:

$$\begin{aligned}\Delta t_{mU} &= t_{mU} - \frac{1}{2}(t_{tU} + t_{bU}), \\ \Delta t_{mD} &= t_{mD} - \frac{1}{2}(t_{tD} + t_{bD}).\end{aligned} \quad (1)$$

However, counters #1 and #8 can never be the middle counter of a triplet given their locations at the top and bottom, respectively, of the counter stack in cart #1. To compute the associated U and D PMT time residuals, we use the following definitions:

$$\begin{aligned} \Delta t_{tU} &= t_{tU} - \frac{1}{2}(t_{mU} + t_{bU} - L/c), \\ \Delta t_{tD} &= t_{tD} - \frac{1}{2}(t_{mD} + t_{bD} - L/c), \end{aligned} \tag{2}$$

$$\begin{aligned} \Delta t_{bU} &= t_{bU} - \frac{1}{2}(t_{tU} + t_{mU} + L/c), \\ \Delta t_{bD} &= t_{bD} - \frac{1}{2}(t_{tD} + t_{mD} + L/c), \end{aligned} \tag{3}$$

where the terms $\pm L/c$ (where $L = 1.5\Delta D/\cos\theta$, with ΔD the nominal vertical separation between counters and θ the track angle relative to the vertical) account for the time difference between the hit in the top (bottom) counter and the average time in the middle/bottom (top/middle) counters.

For the eight counters in cart #1, the measured time resolutions using CFD readout and LED readout without time-walk corrections can be directly compared. The measured time resolutions for each counter are determined using the same residual definitions as in eqs.(1) to (3) for the U and D PMTs with the average counter times replacing the individual PMT times. For the middle counter in each triplet for example, the counter time residuals are defined as:

$$td_m = t_m - \frac{1}{2}(t_t + t_b), \tag{4}$$

with the average counter times relative to the trigger given by:

$$t_t = \frac{1}{2}\left(t_{tU} + t_{tD}\right), t_m = \frac{1}{2}\left(t_{mU} + t_{mD}\right), t_b = \frac{1}{2}\left(t_{bU} + t_{bD}\right).$$

These time residuals compare the average time measured for a reference counter to the average time for the same event from the two neighboring counters in the triplet. The width of this difference distribution, δtd_m, provides a measure of the nominal counter timing resolution through the relation:

$$\sigma_{counter} = \frac{2}{\sqrt{6}}\delta td_m, \tag{5}$$

as derived in Section 5.1 of CLAS12-Note 2013-001.

Fig. 4 shows the measured time resolutions for counters #1 $\rightarrow$ #8 using CFD readout to those using LED readout without time-walk corrections. The time-walk effects when triggering on cosmic ray muons affect the counter time resolution at the level of $\sim$50 ps when summed over all ADC (greater than channel 500 - see Fig. 5) and over all coordinates and angles.

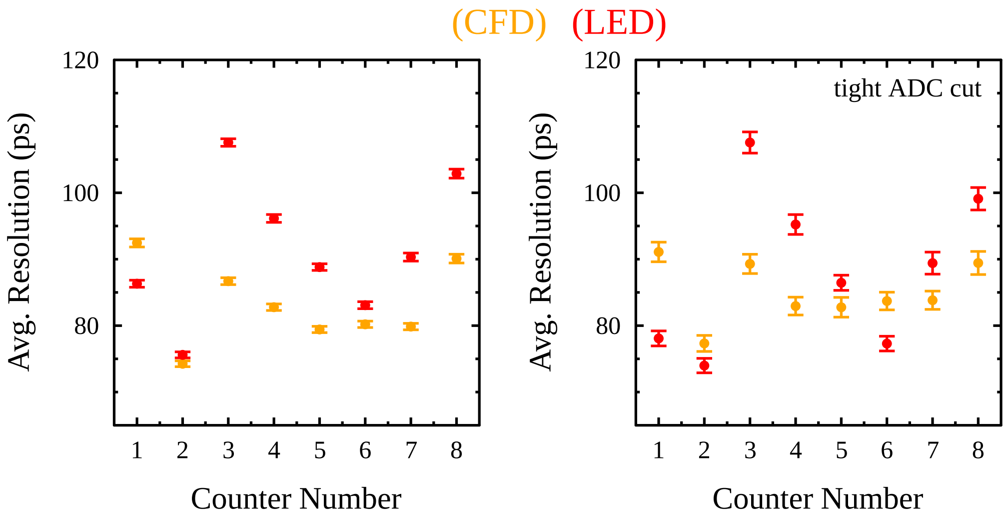

Figure 4: Comparison of measured time resolutions (ps) for counters #1 $\rightarrow$ #8 with CFD readout (orange points) and with LED readout (brown points) without any time-walk corrections. This plot was made requiring for each counter that the minimum PMT ADC value was greater than 500.

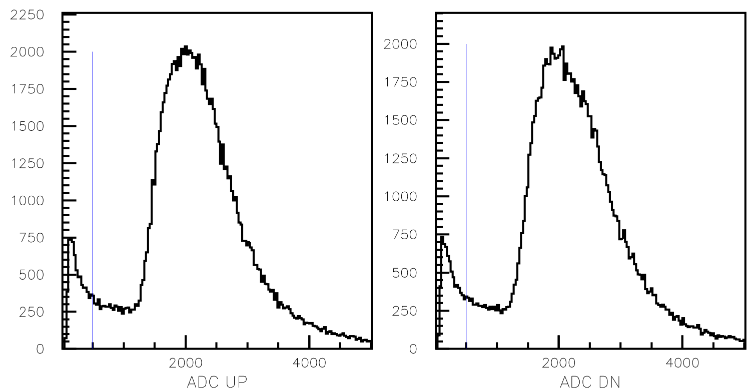

Figure 5: U and D ADC distributions for a representative CTOF counter. All PMT high voltage settings have been gain matched to each other with the mean ADC positioned in ADC channel 2000. A minimum ADC cut of 500 has been applied for the counter time resolution studies.

3.2 Fitting Walk Functionals

The time-walk functional can be determined for each PMT from a fit of the associated time residual vs. ADC distributions. Fig. 6 shows the time residual vs. ADC for the eight upstream PMTs in cart #1. The distributions for the downstream PMTs look similar. These plots include a coordinate cut of ± 10 cm about the center of the counters.

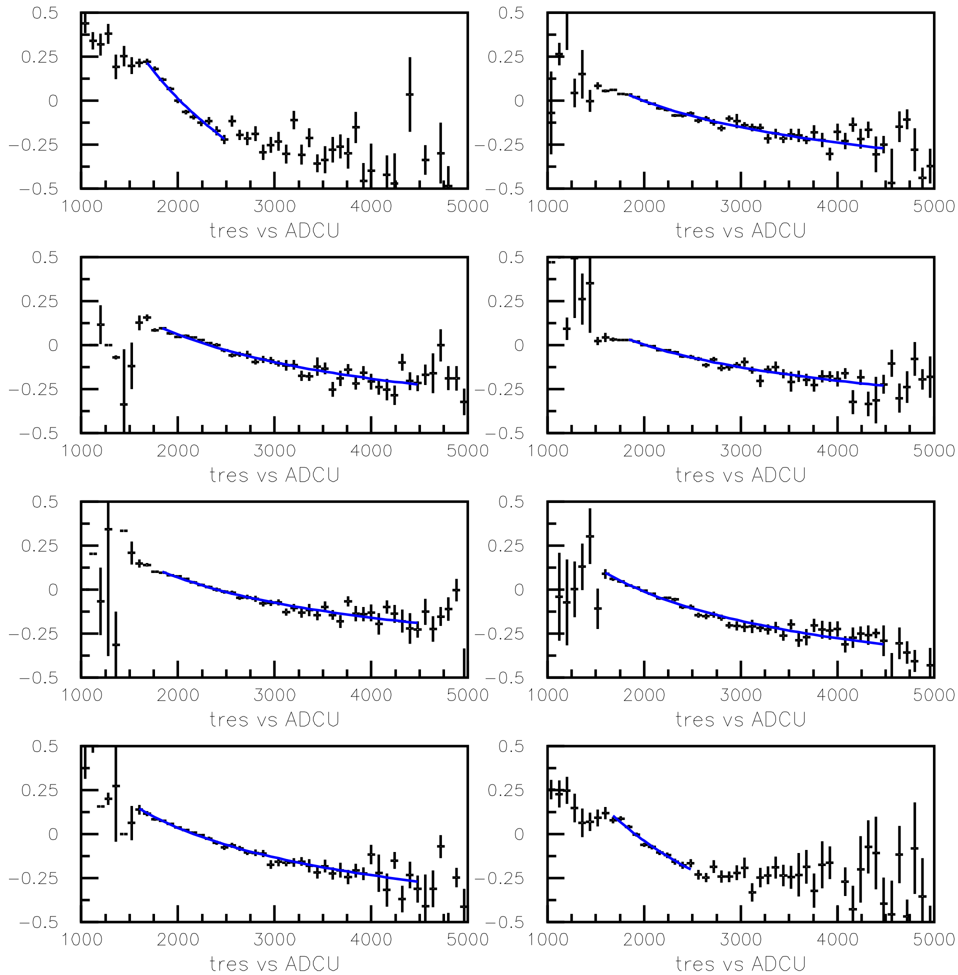

Figure 6: Plot of the measured time residuals (ns) vs. ADC for the upstream PMTs in cart #1. The blue curves represent a fit with the functional form of eq.(6). Data include a ± 10 cm coordinate cut.

Fig. 6 clearly demonstrates the time-walk effects through the deviation of the residual from zero as a function of the ADC value. Note that the time-walk effects are maximal for the low energy deposition minimum ionizing events. Here the scale of the spread of the time-walk effects is seen to be on the order of up to 500 ps.

The nominal functional form used to fit the residual vs. ADC distributions to determine the time-walk correction is defined as:

$$tw = \frac{A}{\sqrt{ADC}} + B \tag{6}$$

Another functional tested was:

$$tw = \frac{A}{B + C\sqrt{ADC}} + D, \tag{7}$$

but this and other similar forms gave quite comparable results for the time-walk corrected counter time resolutions.

A comparison of the time residual vs. ADC distribution for PMTs readout with LEDs to those readout with CFDs is shown in Fig. 7. Here the residuals for the channels using the CFDs are wholly independent of ADC.

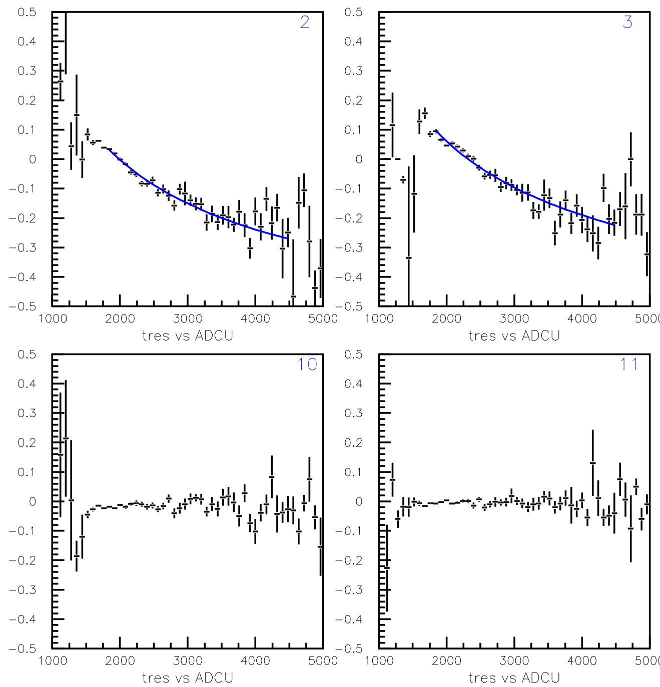

Figure 7: Plot of the measured time residuals (ns) vs. ADC for the upstream PMTs for counters #2 and #3 in cart #1 (readout through LEDs) (top) compared to those for the upstream PMTs for counters #10 and #11 in cart #2 (readout through CFDs) (bottom).

3.3 Correcting the Measured Times

Each measured PMT time relative to the trigger time is corrected using the determined time-walk functional as:

$$t'_U = t_U - tw_U, \tag{8}$$

$$t'_D = t_D - tw_D. \tag{9}$$

Using these time-walk corrected times t', new timing residuals can be computed to check the effect of the corrections. The time-walk corrected residuals for the middle U and D PMTs are given by:

$$\Delta t'_{mU} = t'_{mU} - \frac{1}{2}(t'_{tU} + t'_{bU}), \tag{10}$$

$$\Delta t'_{mD} = t'_{mD} - \frac{1}{2}(t'_{tD} + t'_{bD}). \tag{11}$$

Fig. 8 shows the analog of Fig. 6 using the time-walk corrected times to define the residuals. The vertical lines show the range over which the time-walk functional was fit, indicating that the corrections are removing the time-walk effects reasonably well in these regions. Fig. 8 again includes the ±10 cm coordinate cut. Fig. 9 shows the same quantities as in Fig. 8 but without any restriction on coordinate. The emergent dependence on ADC indicates that the optimal time-walk parameters are not fully independent of coordinate.

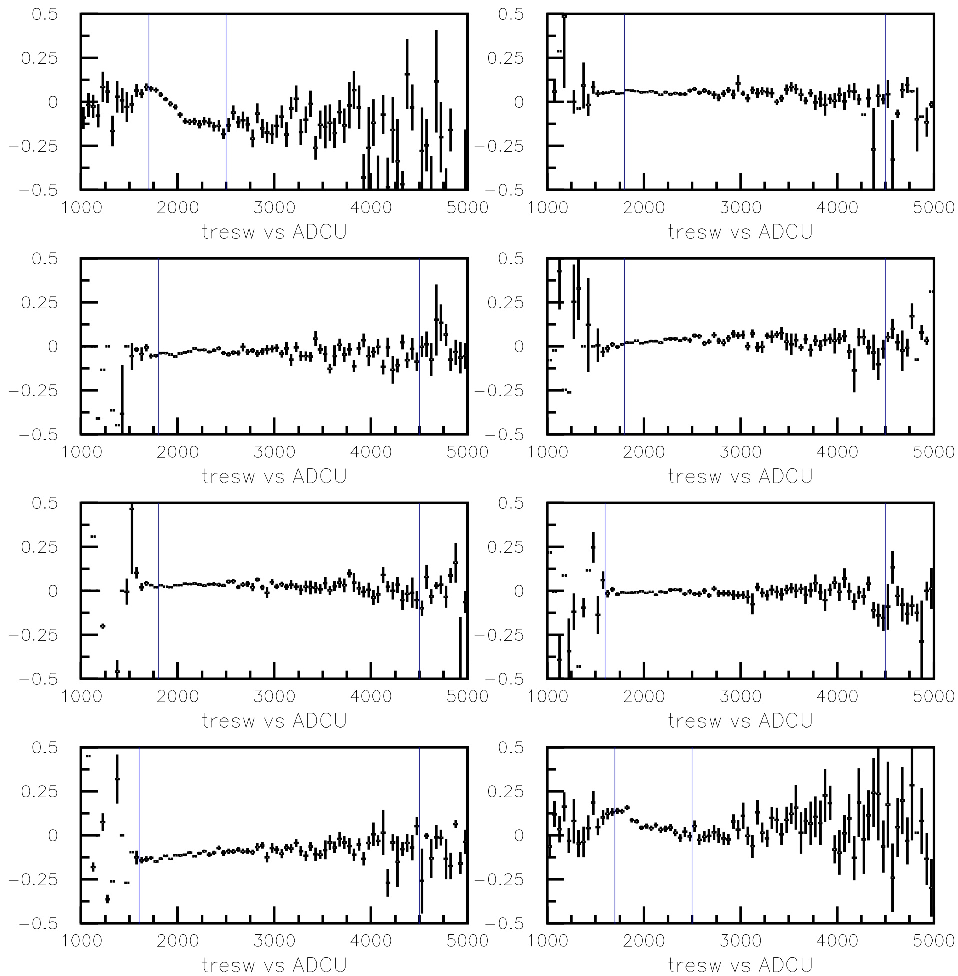

Figure 8: Plot of the time-walk corrected time residuals (ns) vs. ADC for the counters in cart #1. The vertical lines define the region over which the time-walk functional was determined. Data include a ±10 cm coordinate cut.

Note that the timing resolutions for the outermost counters in each cart are consistently seen to be worse compared to the inner counters. This is due to the fact that their measured time is not the direct average of the other two counters used to define their time residuals as shown in eqs.(2) and (3). It turns out that the L/c correction terms include an uncertainty due to the fact that the reconstructed coordinates used to determine the track angle θ are based on TDC times that include time-walk effects. However, the biggest factor limiting the accuracy of the L/c correction terms, which affects all of the top and bottom counters in

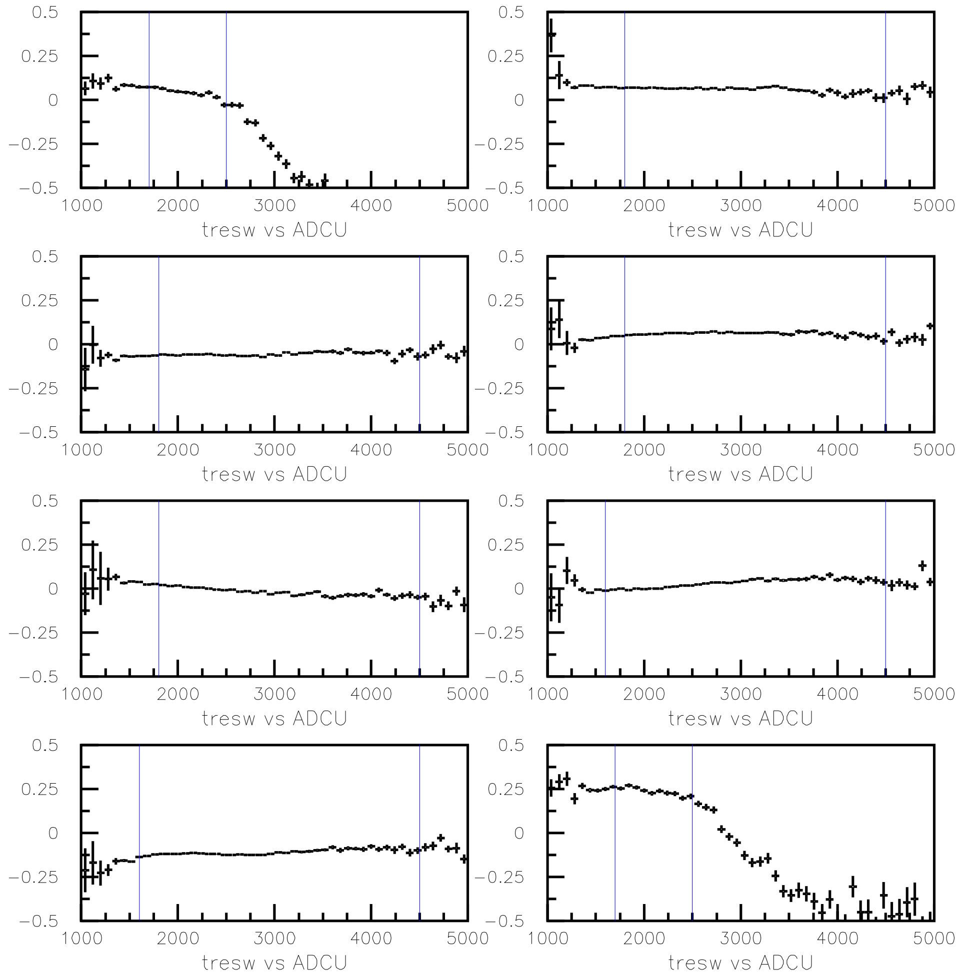

Figure 9: Plot of the time-walk corrected time residuals (ns) vs. ADC for the upstream PMTs for the counters in cart #1. The vertical lines define the regions over which the time-walk functional was determined. Data include no coordinate cut.

the carts regardless of whether they are readout with LEDs or CFDs, is that the counter alignment (in terms of counter-to-counter separation and colinearity) is accurate only to the level of about ± 0.25 in. Fig. 10 shows two dimensional plots of the time residual vs. ADC to highlight the issues with the outermost counters in each cart.

3.4 "Cross-Talk" Effects

The t_U and t_D residuals defined in eqs.(1) to (3) actually are affected by the time-walk effects for all three PMTs that are used in the definitions and not just that of the reference counter. Fitting the functional for the residual vs. ADC defined from the triplet of times and then ascribing the deviation of the residual from zero as the time-walk for the reference PMT is therefore not fully proper.

Performing a global simultaneous parameter determination that minimizes all timing resolutions would, in principle, allow for an optimized parameter set. However, given the number of parameters involved and the limited statistics of the data, this approach is not tenable. The technique that has been chosen to minimize the time-walk functional "cross

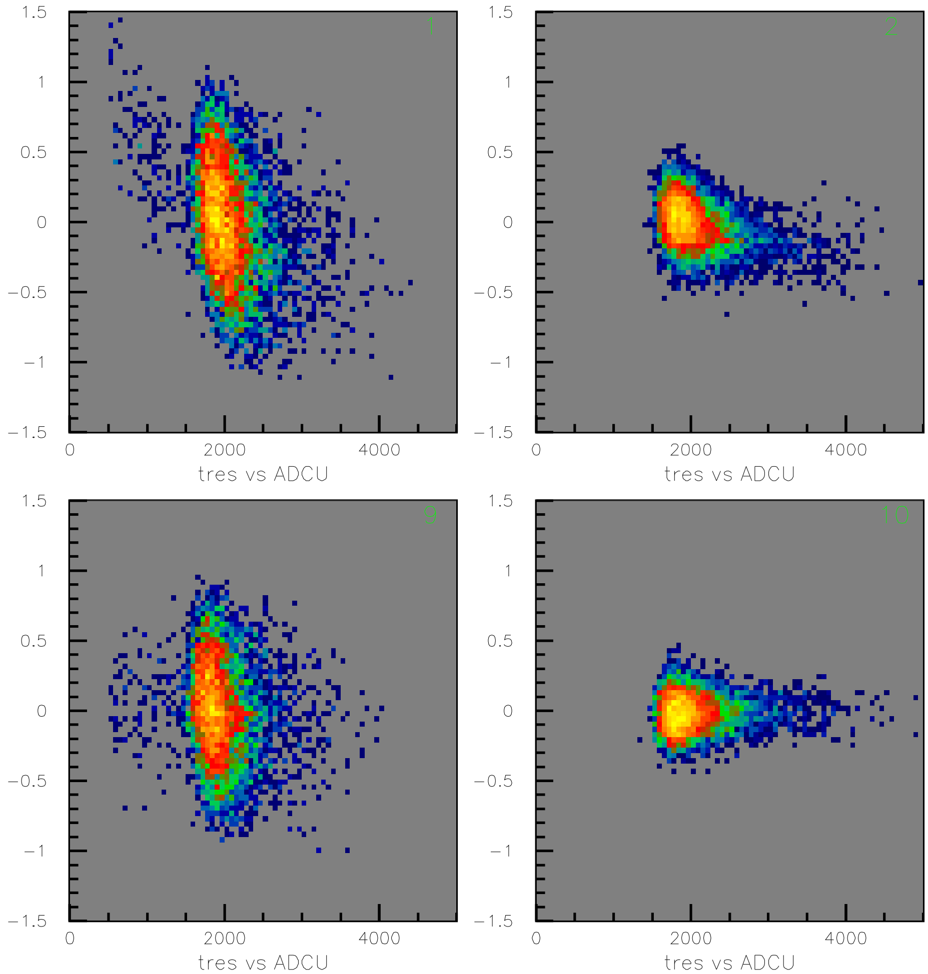

Figure 10: Plot of the time residuals (ns) vs. ADC for the upstream PMTs for counters #1 and #2 in cart #1 (using LEDs) (top) and counters #9 and #10 in cart #2 (using CFDs) (bottom). The width of the residual for the outermost counters in each cart is affected predominantly by the inaccuracy of the geometrical alignment.

talk" among the PMTs is to set the parameters for all PMTs except for one reference PMT to a nominal starting value of A=40 (see eq.(6). The time-walk parameter for this reference PMT is then swept over a broad range of the parameter space to find the value that minimizes the time resolution for that counter (see Fig. 11). This parameter is then fixed and the next PMT is chosen as the reference and the procedure is repeated stepping through all 16 PMTs in cart #1. Using this procedure the time-walk parameters determined for each PMT in cart #1 that result in the optimal counter timing resolutions including the minimum ADC cut of 500 and a $\pm$10 cm coordinate cut are given in Table 1. Note that the parameters for the downstream ends of the counters were determined after those for the upstream ends of the counters.

During the studies of the time-walk corrections for the FTOF panel-1b system at USC, a procedure was developed to effectively separate the time-walk "cross talk" for the six PMTs used in the triplet determination of the counter timing resolution. The procedure selected one of the PMTs of the middle counter in each triplet as the reference counter. The time-walk corrected differences t_{corr} of the other five PMTs in the triplet relative to the reference

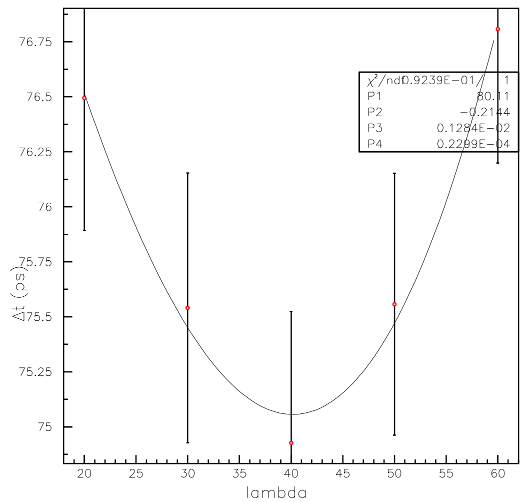

Figure 11: Plot of the counter timing resolution (ps) for counter #2 vs. time-walk parameter A_{2U} from eq.(6) with all other time-walk parameters fixed. Here $A_{2U} \sim 40$ gives the best counter resolution. A second order polynomial fit gives the final value for A_{2U}.

	1	2	3	4	5	6	7	8
U	40.35	37.78	41.75	38.60	45.02	41.99	46.52	33.26
D	41.48	31.58	44.83	38.62	38.01	42.42	35.23	46.98

Table 1: Time-walk parameters A determined for each PMT in cart #1 that yield the best counter timing resolutions for the coordinate range within ± 10 cm. See text for details.

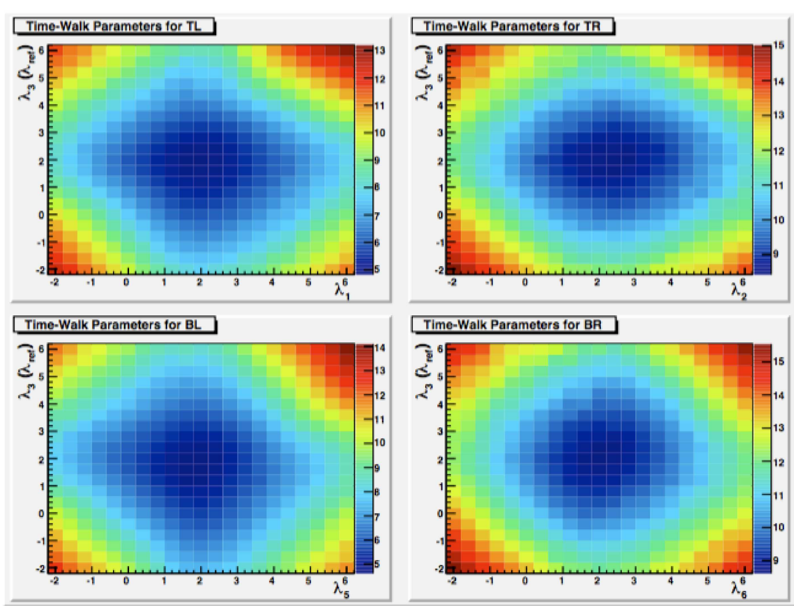

Figure 12: Plots of the FTOF time-walk parameter λ_3 (reference PMT) vs. λ_i for $i = 1, 2, 5, 6$ (called A in the CTOF studies) with the z scale given by $\sigma_{t_{corr}}$ of eq.(12). The plots include a narrow coordinate cut of ± 1.5 cm about the center of the counters.

PMT defined as:

$$t_{corr} = \left(t_i - \frac{\lambda_i}{\sqrt{ADC_i}}\right) - \left(t_{ref} - \frac{\lambda_{ref}}{\sqrt{ADC_{ref}}}\right), \tag{12}$$

were studied over a broad range of time-walk parameters λ_i. Here λ_i (for $i = 1, 2, 4, 5, 6$) and λ_{ref} (for i=3) are the time-walk parameters (called A in the CTOF function) for the six PMTs. For each ionizing particle path, the time with respect to a correlated trigger time is ideally fixed. Thus the spreading of the values of t_{corr} on a specified path must be minimized with the two-parameter correction function for each PMT relative to the reference PMT. Fig. 12 illustrates from FTOF cosmic ray data how the minimization process is carried out. Shown are the correlation plots of λ_3 vs. λ_i for $i = 1, 2, 5, 6$. Here the z color scale represents the width of t_{corr} (i.e. $\sigma_{t_{corr}}$). Note that the procedure shown here displays the TDC values in channels, not in ns as is done for the CTOF studies. Also the λ values shown are scaled by a factor of 10^{-3}. The color scale runs from narrow widths in blues to larger widths in reds. The minimum value of λ is roughly 1.8 from these FTOF studies, which corresponds to a value of roughly 40 for the CTOF studies (1.8 * 10^3 * 24 ps/ch * 10^{-3} ns/ps). Note that the correlation plot of λ_3 vs. λ_4 (the U and D ends of the middle counter) shown in Fig. 13 does not show a local minimum as the values are fully correlated. Fixing the value of λ_3 automatically fixes the value of λ_4.

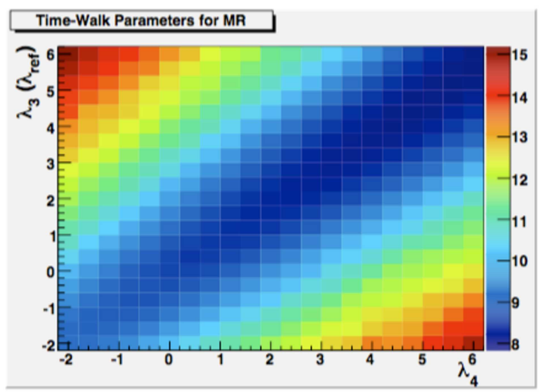

Figure 13: Plot for FTOF of λ_3 (reference PMT) vs. λ_4 (called A in the CTOF studies) with the z scale given by $\sigma_{t_{corr}}$ of eq.(12). The plot includes a narrow coordinate cut of ±1.5 cm about the center of the counter.

The corresponding contour plots of Figs. 12 and 13 for the CTOF system are shown in Fig. 14. These figures were made with a coordinate cut of ±2 cm about the middle of the counters. While the plots are statistics and systematics limited, they still show that the resolutions are minimized for values of A (or λ) of ∼40 as shown in Table 1. Note that the propagation time over the ±2 cm coordinate extent (up to ∼250 ps) is much larger than the resolution differences due to time-walk effects across this range. It is seen that the variations of $\sigma_{t_{corr}}$ across the parameter space are quite limited as shown in the corresponding 3D plots in Fig. 14 and the local minima are quite shallow. However, we can conclude from carrying out this study, that the nominal approach discussed above for minimization of the time-walk "cross-talk" effects for the CTOF analysis is not unreasonable.

Note that using this correction approach (i.e. that shown in Fig. 14) to determine the optimal set of time-walk parameters is not practical given the lack of smoothness of the parameter space that results in many local minima. The data used to prepare Fig. 14 resulted from a 2-week-long data run. Opening the coordinate cut to increase statistics only leads to propagation time effects completely overwhelming the time-walk effects.

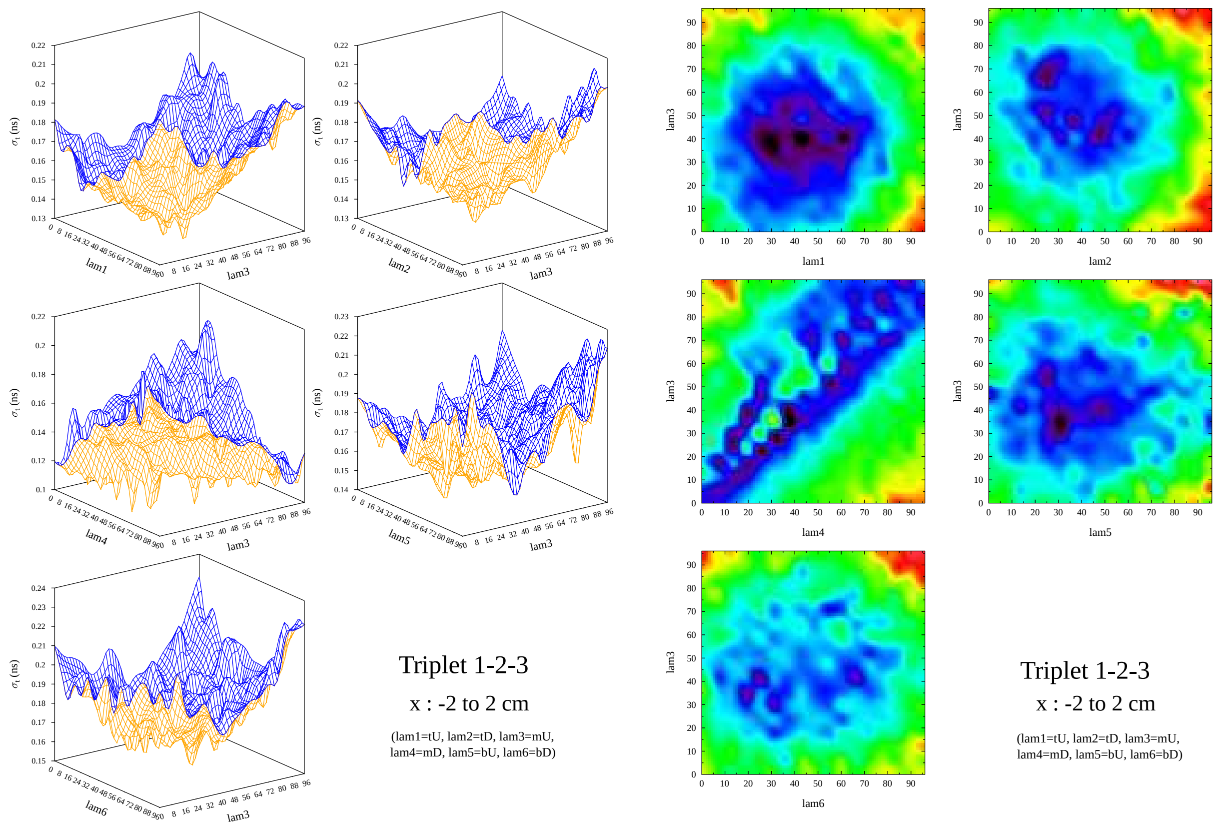

Figure 14: Plots of λ_3 (reference PMT) vs. λ_i for $i = 1, 2, 4, 5, 6$ (the A parameter of eq.(6)) with the z scale given by $\sigma_{t_{corr}}$ of eq.(12) from the CTOF cosmic ray data. These plots include a coordinate cut of ± 2 cm about the centers of the counters. (left) Contour plots. (right) 3D plots.

4 Results

After the application of the time-walk corrections as described above, the time resolution of the counters using LED readout can be compared to that for the nominal counter readout using CFDs. Fig. 15 shows the direct comparison for counters #1 $\rightarrow$ #8.

Note that the results with the LED readout include a coordinate cut of ± 10 cm. Fig. 15 shows that the timing resolution for the counters readout with the LEDs agrees with that for the counters readout with the CFDs to within 7% (with the exception of counter #3 which is slightly worse). Further restricting the event sample to those within the muon peak in the ADC distributions gives fully consistent resolutions between the two discriminator readouts.

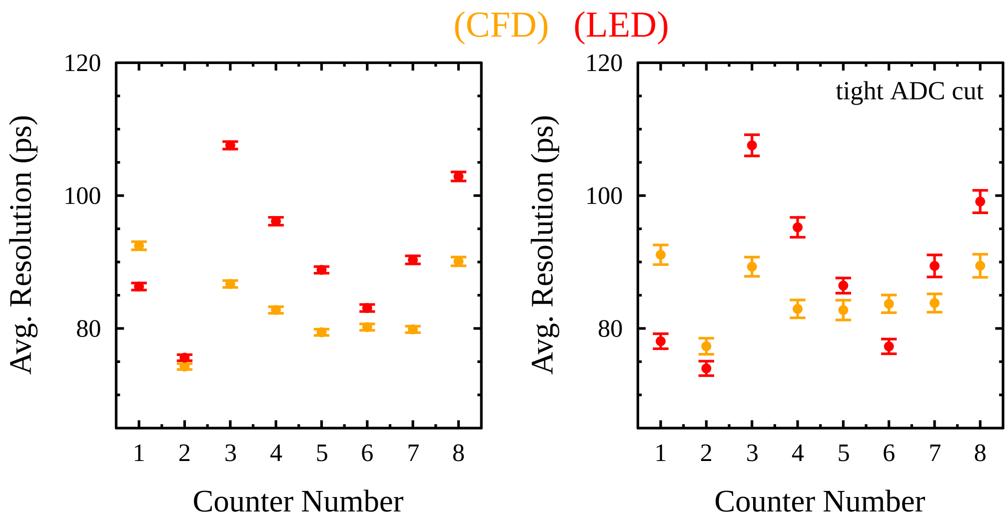

Figure 15: Comparison of measured time resolutions (ps) for counters #1 → #8 with CFD readout (orange points) and with LED readout (brown points) including the time-walk corrections. The LED readout data includes a coordinate cut of ±10 cm. (left) Requires minimum ADC values of 500. (right) Requires only events in the ADC range from 1800 to 2200 about the peak of the minimum ionizing muons (see Fig. 5).

Removing the coordinate cut on the counters for the LED timing resolution studies, gives roughly a 13% worse resolution than compared with the CFD readout setup.

5 Conclusions

Studies of time-walk corrections have been carried out for the CTOF counters using leading edge discriminators. These studies were undertaken to understand if comparable counter timing resolutions using LEDs with time-walk corrections and CFDs could be achieved. The studies showed that for a limited range of coordinates and with a minimum ADC cut of 500, the timing resolution with LED readout could be made comparable to that with CFD readout. However, over the full coordinate range and full ADC range, the resolution achieved with the CFD readout was about 13% better than for the LED readout. There are at least four factors limiting the time resolutions for the counters readout with LEDs. These include:

- Statistics: The readout configuration with the 3-cm-wide CTOF counters in a vertical stack with counter separations of ∼22 cm results in a very low event rate that causes statistical precision to limit the analysis.
- Geometrical mis-alignments: The counters in each of the six CTOF storage carts are only aligned to the level of ±0.25 in. The smears the time residuals given that the counters are not parallel.
- Time-walk "cross talk": The residual definitions include the PMTs from three counters, with each PMT time smeared by time-walk effects. The procedure to isolate the time-walk contributions of a single PMT is not fully optimal.
- Coordinate dependence of the time-walk parameters: The studies of the time-walk parameter dependence on counter hit coordinate carried out for the FTOF panel-1b

scintillators at USC showed smooth time-walk parameter variations of a factor of two from the ends of the bar to the middle of the bar. For the CTOF, similar studies were performed but no such trends were found. However, the width of the coordinate cuts required by the statistics and the cross-talk effects likely muddy the waters here such that coordinate-dependent effects are not seen within the systematic uncertainties in the approach employed.

The current plan is still to employ CFD readout for the CTOF within CLAS12. However, the ADC dependence of the timing resolution will be studied to see if ad hoc corrections need to be applied to further optimize the timing resolutions. Note that ad hoc corrections must be employed as the use of CFDs "destroys" the usual $1/\sqrt{ADC}$ time-walk dependence seen with LED readout.

In 2015 it was found that a number of the CTOF scintillation bars were badly affected by crazing issues. These effects were seen most clearly in highly distorted ADC distributions compared to bars with no crazing effects. The crazing effects resulted in significant loss of light at the PMTs with strong coordinate-dependence to the ADC distributions. The nature of surface crazing is that under some conditions it can continue to propagate along the surface of a scintillation bar. For badly crazed bars, the CTOF time resolution was found to be affected only at the level of 10-15% when CFD readout was employed (comparing the time resolution for the crazed bars to those without surface issues). However, if LED readout were to be employed for the CTOF system in a situation with diminishing scintillation bar surface quality vs. time, then making ADC-based timing corrections to maintain a given timing resolution across the 1-m-long CTOF scintillation bars is more than a bit dangerous.

The final thing to note is that the CTOF time-walk corrections (should LEDs ever be used for the readout scheme) determined in situ within the solenoid would not be carried out using any of the procedures included in this note as the triplet configurations are unique to the setup in the CTOF storage carts. Instead, the nominal approach would be to compute the hit time from tracking through the SVT and/or SVT/MM systems compared to the hit time from the counter. The hit time from the counter would be affected by time-walk effects while that from the tracking systems would not be. In that case, a time residual given by the difference of the CTOF time and that from tracking could be studied vs. ADC. Then appropriate time-walk functionals could be fit and the times corrected.