Description of the Calibration Algorithms for the CLAS12 Central Time-Of-Flight System

D.S. Carman, Jefferson Laboratory
L. Clark, University of Glasgow
R. De Vita, INFN Sezione di Genova
ctof_calib.tex

June 30, 2022

Abstract

This document details the algorithms for the energy loss, PMT gain, and the timing calibrations for the CLAS12 CTOF system.

1 Introduction

The Central Time-of-Flight (CTOF) system is a major component of the CLAS12 Central Detector used to measure the flight time of charged particles emerging from beam-related interactions in the target. The CTOF detector is positioned inside the 5-T superconducting solenoid magnet surrounding the target and consists of 48 scintillation bars with double-ended readout that form a hermetic barrel. A detailed description of the CTOF system is provided in Ref. [1]. There are two parts of the system calibration. The first is used to gain match the system PMTs. This portion of the calibration uses the ADC information for the upstream and downstream PMTs of each counter to gain balance the PMTs using incident minimum-ionizing particles. The reconstruction code uses the average counter ADC value to compute the energy deposited in each bar dE/dx for a passing charged particle track, accounting for the path length through the bar extrapolating the track beyond the Central Vertex Tracker (CVT). The second part of the calibration determines the charged particle flight time from the reaction vertex. This portion of the calibration is a multi-step process that must be completed in a specific order. A detailed description of the full set of CTOF calibration constants is provided in Ref. [2].

2 Gain Calibrations

There are four parameters associated with the gain balancing constants for each FTOF counter. These parameters are:

- *mipa* - Centroid of the Landau peak in the ADC geometric mean histogram for minimum-ionizing particles
- *mipa_err* - Uncertainty in the Landau peak centroid in the ADC geometric mean histogram for minimum-ionizing particles
- *logratio* - Mean of the ADC logarithmic ratio distribution
- *logratio_err* - Uncertainty in the mean of the ADC logarithmic ratio distribution

Even though there are separate *mipa* parameters for the upstream and downstream PMTs of each counter, *mipa_upstream* and *mipa_downstream* are filled with the same fit centroid for the minimum-ionizing peak for the geometric mean ADC distribution. The parameters also include the uncertainties in the determination of the geometric mean (where *mipa_upstream_err* = *mipa_downstream_err*) and the ADC log ratio (*logratio_err*) distributions.

2.1 Geometric Mean

The `GMEAN` algorithm is used to determine the minimum-ionizing peak position of the ADC geometric mean distribution for each CTOF counter in units of ADC channels. The calibration focuses only on the minimum-ionizing particles (which dominate the tracks associated with each event). As these tracks pass through the magnetic field of the solenoid and are broadly distributed in kinematics, the tracks are not typically normal to the face of the CTOF counters. For these events, a path length correction in the CTOF counter is applied within the CTOF calibration suite using CVT tracking information. The ADC geometric mean for each counter is defined as:

$$\overline{ADC} = \sqrt{(ADC_U - PED_U) \cdot (ADC_D - PED_D)}, \tag{1}$$

where $PED_{U,D}$ represent the ADC channel pedestal values. With the available CVT tracking information, the path-length-corrected geometric mean is given by:

$$\overline{ADC}' = \overline{ADC} \cdot \frac{t}{P}, \tag{2}$$

where t is the CTOF counter thickness (t=3 cm) and P is the track path length within the counter (from the track entrance point on the counter to its exit point on the counter). P uses the CVT track extrapolated past the CVT to the CTOF location using the CTOF counter positions and dimensions from the CLAS12 geometry service.

The algorithm fits the geometric mean spectrum for each counter with a composite function of a Landau signal and an exponential background using:

$$GMEAN = c_1 \cdot p(\overline{ADC}') + c_2 \cdot \exp(c_3\overline{ADC}'), \tag{3}$$

with fit constants c_i. Figure 1(left) shows an ADC geometric mean plot for one representative CTOF counter with the fit functional overlaid. The `GMEAN` algorithm requires $\overline{ADC}' > 0.25$ times the targeted minimum-ionizing peak channel.

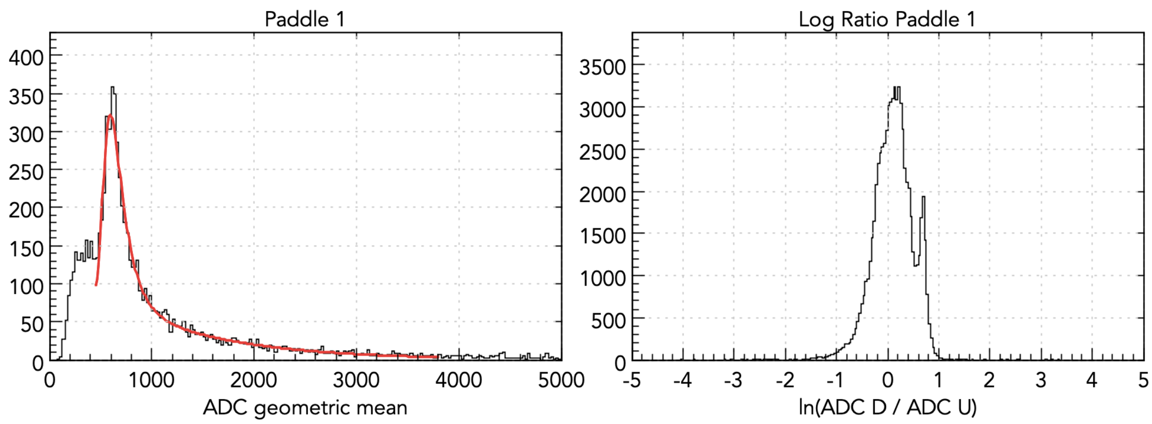

Figure 1: (Left) ADC geometric mean distribution with the fit result overlaid and (right) ADC log ratio distribution for one representative CTOF counter.

2.2 ADC Logarithm Ratio

The LOGRAT algorithm is used to find the mean of the logarithm of the ratio of the counter ADCs defined as:

$$\mathcal{R} = \log\left(\frac{ADC_D - PED_D}{ADC_U - PED_U}\right). \tag{4}$$

In forming the ADC log ratio (see Fig. 1(right)), there is no event selection beyond the trigger condition and the minimum $\overline{ADC}'$ cut described in Section 2.1. The algorithm fills a histogram with the logarithm of the ADC ratio. The mean (*logratio*) and its uncertainty (*logratio_err*) are the returned values.

2.3 PMT High Voltage Determination

Once the minimum-ionizing peak location in the ADC geometric mean distribution and the centroid of the ADC log ratio distribution are determined for the counter, the algorithm computes the necessary PMT high voltage settings to gain balance the upstream and downstream PMTs to each other and to position the minimum-ionizing peak in the ADC geometric mean distribution in the desired position in the ADC spectrum.

The high voltage values for the upstream and downstream PMTs are computed first by determining the $ADC_{U,D}$ minimum-ionizing peak centroids $G_{U,D}$ from the $\overline{ADC}'$ and $\mathcal{R}$ values as:

$$G_U = \frac{\overline{ADC}'}{\sqrt{\exp \mathcal{R}}}, \qquad G_D = \overline{ADC}' \cdot \sqrt{\exp \mathcal{R}}. \tag{5}$$

Next the required high voltage values are computed using:

$$\Delta V_{U,D} = \frac{V_{U,D}^{orig} \cdot (ADC_{MIP} - G_{U,D})}{G_{U,D} \cdot \alpha}, \tag{6}$$

$$V_{U,D}^{new} = V_{U,D}^{orig} + \Delta V_{U,D}, \tag{7}$$

where ADC_{MIP} is the desired channel for the minimum-ionizing peak centroid in the $\overline{ADC}'$ spectrum, V^{orig} (V^{new}) is the starting (new) PMT high voltage value, and α is the PMT power law gain factor (α=4.0). The code checks the computed values to ensure $|HV^{max}| <$ 2500 V for the PMTs. If $|HV^{new}| > |HV^{max}|$, the program sets $HV^{new} = HV^{max}$. Also as a further safety consideration to protect the hardware, the program limits changes in $|\Delta V|$ to no more than 250 V. The calibration suite creates a BURT output file with the new PMT high voltage (HV) settings for download into the CAEN HV mainframe through the EPICS Slow Controls system.

2.4 Energy Loss

The energy loss in the counter for crossing charged particle tracks is determined from the gain balancing calibration parameters in the CTOF reconstruction code. The following steps are used to determine the energy loss:

- Compute the ADC channel-to-energy conversion factor using:

$$\mathcal{K} = \left[\frac{\left(\frac{dE}{dx}\right)_{MIP} \cdot t}{ADC_{MIP}} \right], \tag{8}$$

  where ADC_{MIP} is the centroid of the minimum-ionizing peak in the geometric mean distribution, $\left(\frac{dE}{dx}\right)_{MIP}$ is the energy loss for minimum-ionizing particles in the scintillation bars (1.956 MeV/cm), and t is the CTOF counter thickness (t=3 cm).

- Compute the deposited energy values measured by the upstream and downstream PMTs for each counter using:

$$E_{U,D} = G_{U,D} \cdot \mathcal{K}, \tag{9}$$

  where $G_{U,D}$ are defined in Section 2.3.

- Correct the energy measured at the upstream and downstream PMTs for attenuation loss effects in each counter using:

$$E_{U,D}^{corr} = E_{U,D} \exp\left(\frac{y_{U,D}}{\lambda}\right), \tag{10}$$

  where $y_{U,D}$ are the distances along the bar from the track hit position to the upstream and downstream PMTs (see Eq.(20) in Appendix A for definitions) and λ is the counter attenuation length determined using the algorithm `ATTEN` in Section 3.2.

- Compute the track energy loss in the counter as the average of $E_{U,D}^{corr}$ using:

$$E_{dep} = \sqrt{E_U^{corr} \cdot E_D^{corr}}. \tag{11}$$

3 Timing Calibration

The timing calibration constants for the CTOF system are determined in a specific sequence. The individual steps are listed in Table 1. The algorithm steps are denoted as: `UD` for the upstream-downstream PMT timing alignment, `ATTEN` for the attenuation length calibration, `VEFF` for the effective velocity calibration, `HPOSB` for the hit-position-dependent bin-by-bin timing shift, `HPOS` for the hit-position-dependent functional timing shift, `RFP` for the RF timing offsets, and `P2P` for the counter-to-counter timing offsets.

Step #	Calibration	Algorithm
1	Upstream-Downstream PMT Timing Alignment	`UD`
2	Attenuation Length	`ATTEN`
3	Effective Velocity	`VEFF`
4	Hit-Position-Dependent Correction - Bin	`HPOSB`
5	Hit-Position-Dependent Correction - Function	`HPOS`
6	Counter RF Time Offsets	`RFP`
7	Paddle-to-Paddle Time Offsets	`P2P`

Table 1: The individual steps for the CTOF timing calibrations.

The timing calibration is completed using CVT information for the track path length reconstruction. After the completion of each of the above steps, the full CTOF timing calibrations are completed. The corrected CTOF hit times reconstructed for the upstream and downstream PMTs for each counter are given by:

$$\begin{aligned} t_U &= (\mathcal{C}_{TDC} \cdot TDC_U) - \frac{\mathcal{C}_{UD}}{2} - \frac{z_U}{veff}, \\ t_D &= (\mathcal{C}_{TDC} \cdot TDC_D) + \frac{\mathcal{C}_{UD}}{2} - \frac{z_D}{veff}, \end{aligned} \tag{12}$$

where z_U and z_D represent the distances along the scintillator from the track crossing point to the upstream and downstream PMT locations, respectively, as defined in Appendix A. The average counter hit time using the timing from the upstream and downstream PMTs for a given counter is:

$$t_{hit} = \frac{1}{2}(t_U + t_D) + t^{HPOSB} + t^{HPOS} + t_{RF}^{pad} + \mathcal{C}_{p2p}. \tag{13}$$

The time t_{hit} represents the charged particle flight time relative to the event start time from the event vertex to the midplane of the CTOF counter associated with the track. Here $\mathcal{C}_{TDC}$ is the TDC conversion time ($\sim$24 ps/channel), TDC is the measured TDC channel, $\mathcal{C}_{UD}$ is the time shift from the `UD` step, t^{HPOSB} and t^{HPOS} are the hit-position-dependent timing corrections from the `HPOSB` and `HPOS` steps, respectively, t_{RF}^{pad} is the RF timing offset from the `RFP` step, and $\mathcal{C}_{p2p}$ is the paddle-to-paddle time offset from the `P2P` step. Figure 2 provides a flowchart of the CTOF timing calibration sequence. Full details on the CTOF timing calibration are included in Ref. [3].

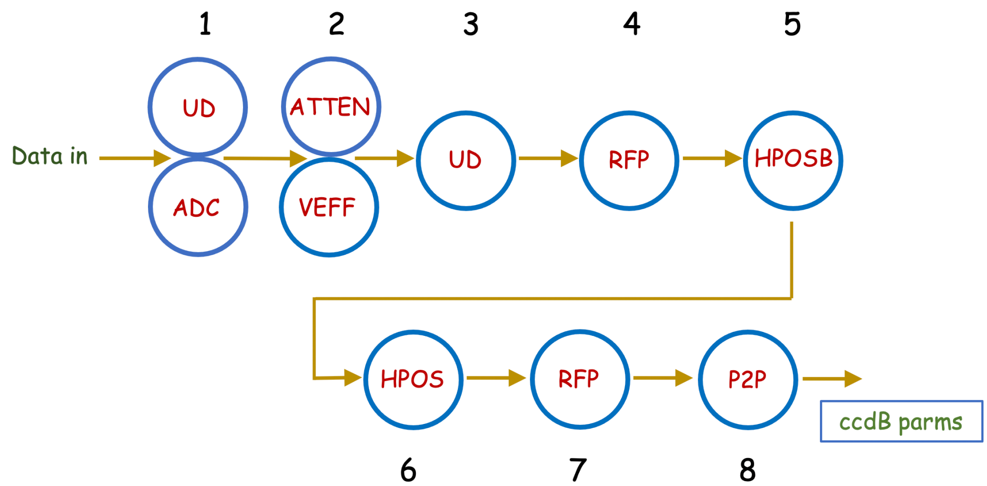

Figure 2: Flowchart detailing the steps and their ordering for CTOF calibration procedure.

3.1 Upstream-Downstream PMT Timing Alignment

The purpose of the upstream-downstream PMT timing alignment algorithm `UD` is to center the TDC time difference distribution for each counter, $t_U - t_D$, about zero. The algorithm compares the hit coordinate along the bar from the upstream-downstream PMT time difference to the coordinate determined from the projected CVT tracks to the CTOF midplane. The histogram used to determine the upstream-downstream time offset is:

$$upstream\_downstream = \frac{2}{veff} \cdot (t_U - t_D) - coor_{CVT}. \tag{14}$$

Event selection is not needed other than the trigger condition. The database parameter is:

- *upstream_downstream* - upstream/downstream PMT TDC time difference (ns)

The algorithm requires the TDC values from both ends of each counter and that both $ADC_{U,D} > 100$. Figure 3(left) shows for a representative CTOF counter the difference between the hit coordinate as determined from the TDC time difference compared to that from the projected track beyond the CVT system. Figure 3(right) shows the upstream/downstream PMT TDC time difference. The correction subtracts half of the timing offset from the upstream TDC time and adds half to the downstream TDC time as shown in Eq.(12).

3.2 Attenuation Length

The attenuation length calibration algorithm `ATTEN` is used to determine the energy attenuation length in each counter. It requires both TDC and ADC information and the effective velocity for the counter. There are three constants associated with the attenuation lengths for each counter.

- *attlen* - attenuation length (cm) for each end of each counter
- *attlen_err* - uncertainty of the attenuation length (cm)

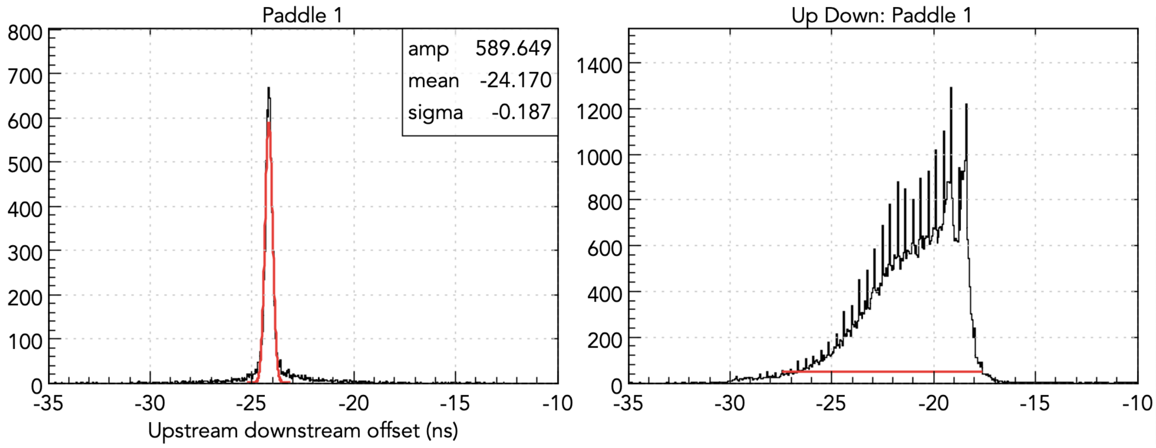

Figure 3: Upstream-downstream time difference distributions (ns) for one representative CTOF counter showing the time difference from (left) Eq.(14) and (right) the upstream-downstream PMT time difference.

- *y_offset* - intercept of attenuation length fit

Although there are attenuation length constants in the calibration constant database for both the upstream and downstream ends of each counter, only a single fit for each counter is performed assuming *attlen_upstream* = *attlen_downstream* = *attlen*. The counter attenuation length is determined using a linear fit to a plot of the ADC log ratio $\mathcal{R}$ vs. coordinate (see Fig. 4) of the form:

$$\log\left(\frac{ADC_D - PED_D}{ADC_U - PED_U}\right) = y\_offset + \frac{2 \cdot coor}{attlen}, \tag{15}$$

where *y_offset* is the y-intercept and *attlen* = 2/slope. The parameter *attlen_err* is the fit uncertainty associated with the attenuation length fit, where *attlen_upstream_err* = *attlen_downstream_err*. No uncertainty for the y-intercept parameter is stored as the intercept parameter is not presently used. In filling the histograms to determine the counter attenuation lengths, no event selection is required beyond the trigger requirement.

The hit coordinate along the CTOF counter (*coor*) is computed from the difference in the measured upstream and downstream counter PMT hit times after the `UD` time offset determination using the expression:

$$coor = \frac{veff}{2} \cdot (t_U - t_D - upstream\_downstream), \tag{16}$$

where *veff* is the counter effective velocity determined using the algorithm `VEFF` described in Section 3.3. For the initial attenuation length estimation, *veff* should be set to values from a previous detector calibration.

3.3 Effective Velocity

The effective velocity is the average speed that scintillation light propagates along the scintillation bars and is determined using the algorithm `VEFF`. There are two constants associated with the measured effective velocity:

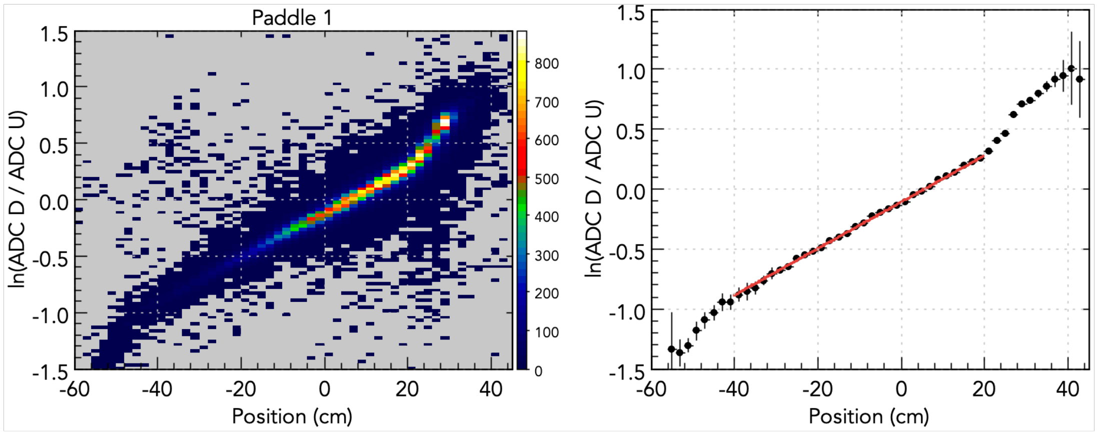

Figure 4: (Left) Plot of the ADC log ratio vs. reconstructed hit coordinate (cm) from the PMT hit times and (right) the corresponding linear fit for a representative CTOF counter.

- *veff* - effective velocity of the counter for each end (cm/ns)
- *veff_err* - uncertainty in the effective velocity (cm/ns)

The effective velocity is determined using a slightly modified definition of the hit coordinate along the counter from that given in Eq.(16):

$$coor_{CVT} = \frac{v_{eff}}{2} \cdot (t_U - t_D - upstream\_downstream). \tag{17}$$

Here the CTOF hit coordinate along the counter is now determined independently from the CVT tracking information projected to the CTOF counter $coor_{CVT}$. The hit position from tracking along the CTOF counter is determined from the extrapolated track coordinate to the mid-point between the track entrance and exit points of the counter. Note that even though the calibration database includes separate constants for *veff_upstream* and *veff_downstream*, a single fit is performed to determine the counter effective velocity assuming *veff_upstream* = *veff_downstream*.

Figure 5 shows the distribution of half the counter upstream/downstream PMT TDC time difference after the `UD` time offset determination for a representative counter plotted versus the CTOF hit coordinate determined from CVT tracking. The effective velocity for the counter is determined from the slope of a linear fit to this distribution. The parameter *veff_err* is the uncertainty in the effective velocity from the fit where the calibration sets *veff_err_upstream* = *veff_err_downstream*. Note that the fits performed to determine the counter effective velocity employ no event selection other than the trigger condition and a matched CVT-CTOF track.

Note that the y-intercept of the effective velocity fit provides a separate measure of the upstream/downstream PMT timing offset that has different systematics than the value derived from the `UD` PMT time difference approach.

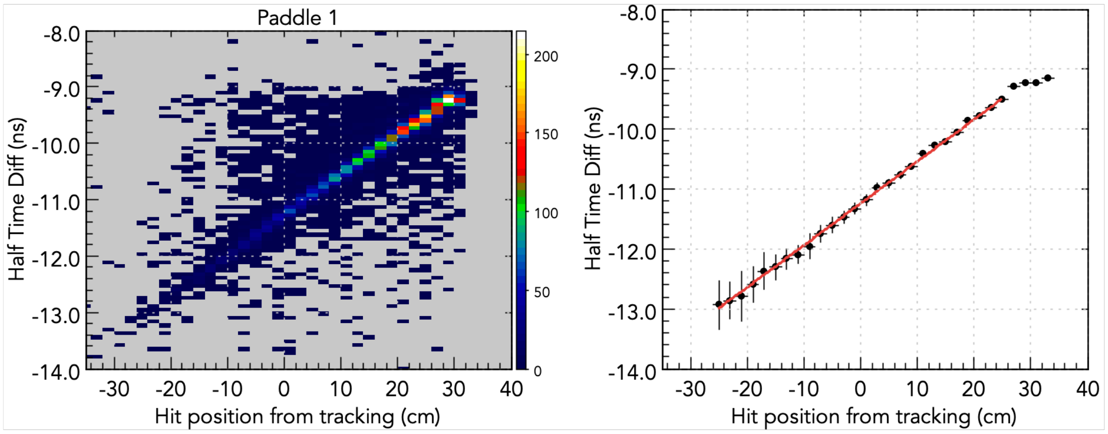

Figure 5: (Left) Distribution of half the upstream/downstream PMT TDC time difference (ns) versus the coordinate (cm) along the counter $coor_{CVT}$ from CVT tracking information and (right) the corresponding linear fit for a representative CTOF counter.

3.4 Hit-Position-Dependent Correction - Bin (HPOSB)

The reconstructed hit time from CTOF has an anomalous shift due to effects associated with the non-rectilinear geometry of the scintillator bars at their ends where they connect to the light guides. This shift is corrected in a two-step process beginning with the `HPOSB` correction. The `HPOSB` calibrations are completed using one 2D histogram for each counter of Δt_V, the event vertex time t_v relative to the event start time, as a function of hit position along the counter determined by extrapolating the CVT track out to the mid-plane of the CTOF counter. The time residual t_R is given by:

- $t_R = mod(\Delta t_v, T_{RF})$ (ns) vs. hit position (cm)
- $\Delta t_v = t_v - t_{start}$
- $t_v = t_{hit} - \frac{L}{\beta c}$
- $t_{start} = t_{RF} + \frac{z_{vert}}{\beta_e c}$.

Here t_{hit} is the average counter hit time defined in Eq.(13) and T_{RF} is the RF period. L is the reconstructed path length from the vertex to the hit position at the counter mid-plane of a charged particle of velocity β. t_{RF} is the RF time for the event defined at z=0 and $z_{vert}/(\beta_e c)$ is a term to correct the RF time to account for the actual electron beam event vertex location. Here the histogram is setup with a bin width of 25 ps in t_R and a bin width of 1 cm in hit position. The modulus is used to account for the beam RF structure and to project all values of Δt_v about $t_R = 0$. The calibration parameters are the bin-by-bin values of t_R needed to center the value of Δt_v for each slice. Figure 6 shows the distributions of t_R vs. hit position before (top) and after (bottom) the HPOSB calibration.

3.5 Hit-Position-Dependent Correction - Function (HPOS)

As noted in Section 3.4, the removal of the remnant time offset in the reconstructed CTOF hit time caused by effects of the CTOF geometry is done in two steps. The first is the

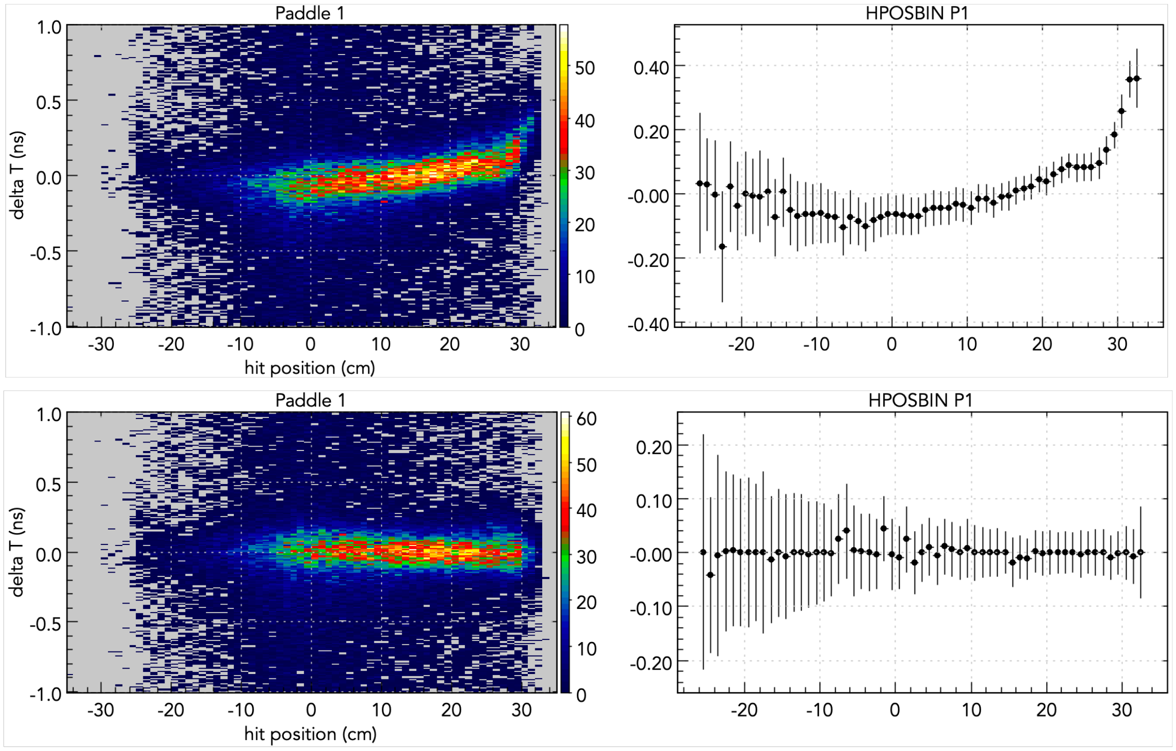

Figure 6: hposbin histograms (top) before and (bottom) after the calibration for one representative CTOF counter. Each row shows the 2D histogram and its associated profile histogram used for the calibration.

HPOSB step that accounts for the major part of the correction. However, due to biases in forming the t_v vs. hit position histogram based on finding the channel for each hit position bin corresponding to the maximum number of counters in t_R, a systematic anomaly still remains. The same histogram used for the HPOSB correction is also used for the second step called HPOS.

There are 2 parameters associated with the HPOS calibration for each counter called *hposa* and *hposb* that are used in the hit-position-dependent - function fit vs. hit position z along the counter:

$$t^{HPOS} = hposa \cdot z^2 + hposb \cdot z + hposc. \tag{18}$$

In this expression, the constant term *hposc* is absorbed into the RFP correction. Figure 7 shows the distributions of t_R vs. hit position after the HPOSB calibration before (top) and after (bottom) the HPOS calibration.

3.6 Counter RF Time Offsets

The RF timing offset algorithm RFP uses one 1D histogram for each counter using the vertex time residual t_R defined in Section 3.4. Here the histogram is setup with a bin width of 25 ps. There is one parameter associated with the RF time offsets and time resolution for each counter:

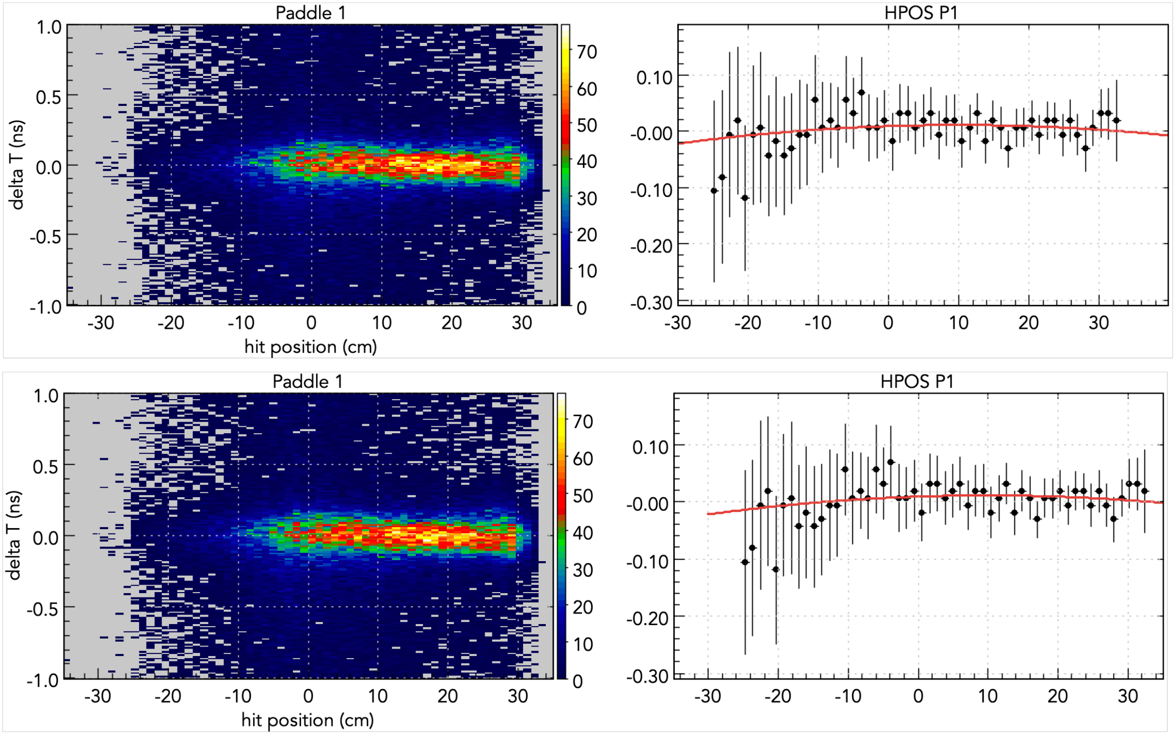

Figure 7: hpos histograms after the `HPOSB` calibration before (top) and after (bottom) the `HPOS` calibration. Each row shows the 2D histogram and its associated profile histogram used to fit to determine the correction parameters.

- *rfpad* - counter time offsets with respect to RF (ns)
- *tres* - effective counter time resolution (ns)

Figure 8 shows the t_R distribution for a representative FTOF counter. The fit function is a Gaussian and a first-order polynominal for the background:

$$f(t_R) = G(t_R, t_{RF}^{pad}, tres) + c_1 \cdot t_R + c_2, \tag{19}$$

where G represents the Gaussian as a function of t_R of centroid t_{RF}^{pad} and width *tres*. c_i are the parameters for the background polynomial.

3.7 Paddle-to-Paddle Time Offsets

The paddle-to-paddle timing offset calibrations are completed using one 1D histogram for each counter that defines a vertex time difference:

- $\Delta t_v = t_{hit} - L/veff - t_{start}$ (ns),

where t_{hit} is the counter hit time as defined in Eq.(13) and t_{start} is the event start time. The term $L/veff$ is the flight time of a charged particle from the event vertex to the hit CTOF counter with the path length L in the solenoid field determined from CVT track

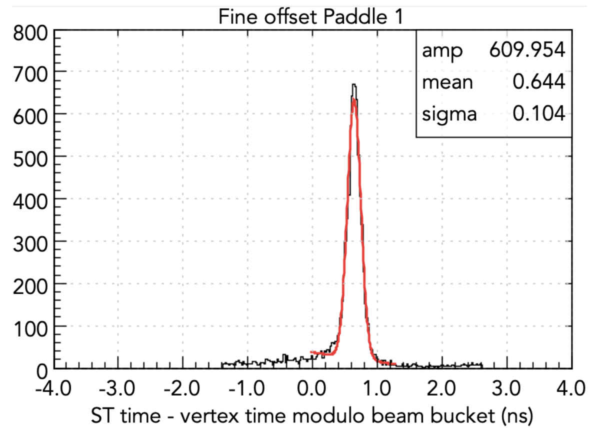

Figure 8: Vertex time distribution for a representative counter. The curve shows the fit functional whose centroid determine the RF timing offset for the counter and whose width provides a measure of the effective counter timing resolution.

reconstructed extrapolated to the CTOF midplane. Here the histogram is setup with a bin width of T_{RF} and the event start time is defined by a coincident forward track. There is one parameter associated with the paddle-to-paddle time offset for each counter

- *paddle2paddle* - counter-to-counter relative time offsets (ns)

Figure 9 shows the t_v distribution before (left) and after (right) the `P2P` step. The algorithm determines the set of timing offsets to set $t_v = 0$ for all counters in the CTOF system. Figure 10 shows the calibration values and the t_v channel with the maximum number of counts before (top) and after (bottom) the calibration. After the calibration has converged, the value of t_V is zero for all counters.

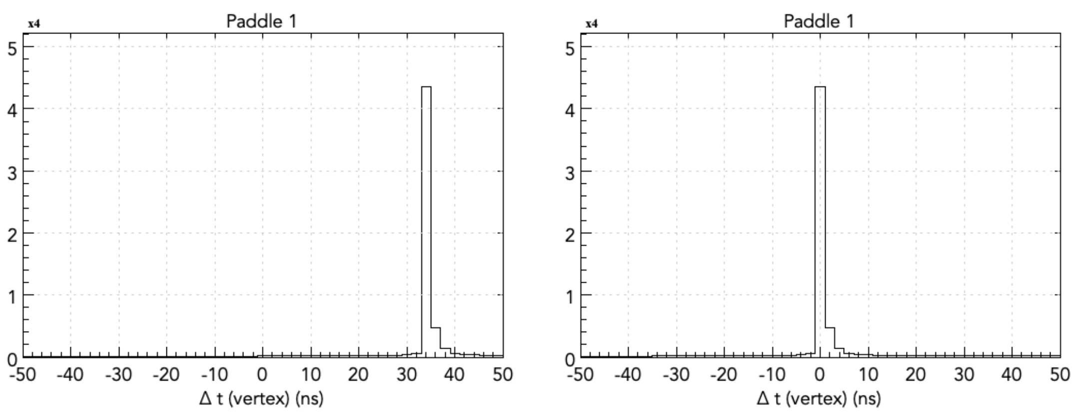

Figure 9: Vertex time difference distribution for charged particle track events relative to the event start time for one reference CTOF counter. The left distribution is before the `P2P` step and the right distribution is after the `P2P` step.

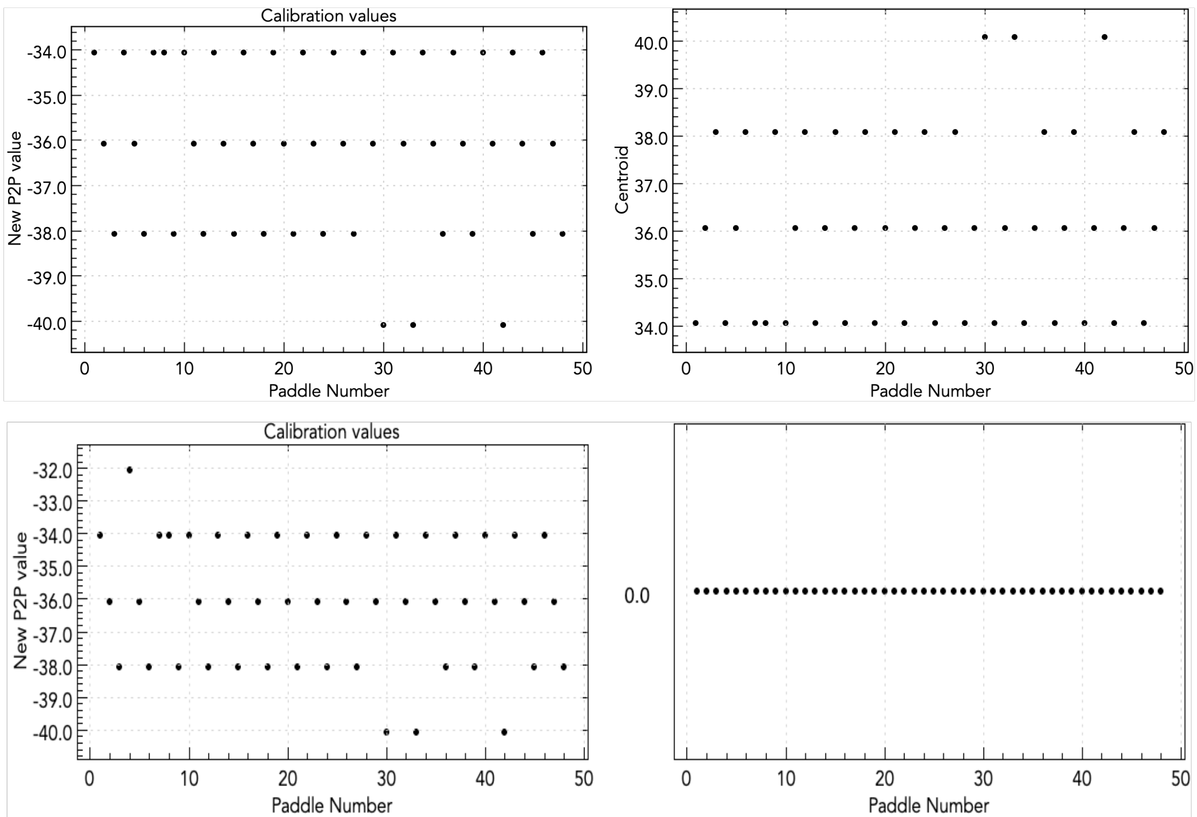

Figure 10: Values for the P2P offsets (left) and t_v values (right) for all CTOF counters before (top) and after (bottom) the calibration.

A CTOF Hit Time and Coordinate Determination

Figure 11 shows a representation of a CTOF scintillation bar with the upstream and downstream PMTs noted. The reconstructed hit coordinate along the bar *coor* is defined with respect to the center of the bar. The distances along the bar from the hit point to the upstream and downstream ends of the bar are given by:

$$z_U = \left(\frac{L}{2} + coor\right), \qquad z_D = \left(\frac{L}{2} - coor\right), \tag{20}$$

where L is the counter length.

The hit times of the passing charged particle can be determined separately from the times t_U and t_D measured by the upstream and downstream PMTs, respectively, and are given by:

$$t^U_{hit} = t_U - \frac{z_U}{veff}, \qquad t^D_{hit} = t_D - \frac{z_D}{veff}. \tag{21}$$

The average hit time is then given by:

$$\begin{aligned}
\bar{t}_{hit} &= \frac{1}{2}(t^U_{hit} + t^D_{hit}) \\
&= \frac{1}{2}\left[t_U - \left(\frac{L}{2} + coor\right)\frac{1}{veff} + t_D - \left(\frac{L}{2} - coor\right)\frac{1}{veff}\right] \\
&= \frac{1}{2}\left[t_U + t_D - \frac{L}{veff}\right].
\end{aligned} \tag{22}$$

The hit coordinate along the bar is given by:

$$coor = \frac{veff}{2}(t_U - t_D - upstream\_downstream), \tag{23}$$

where *upstream_downstream* is the upstream-downstream timing alignment parameter defined in Section 3.1.

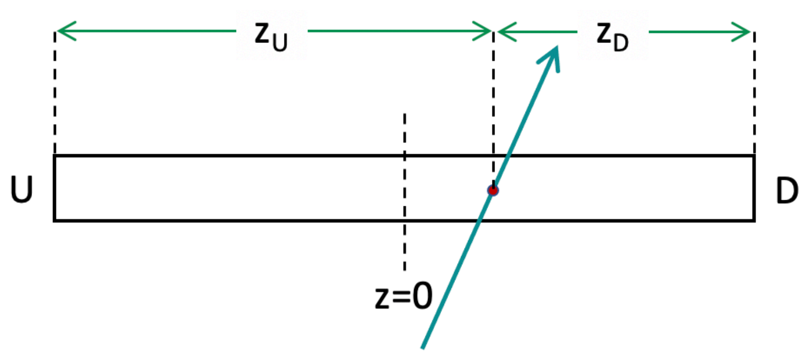

Figure 11: Definition of the hit distances d_U and d_D from the hit position of the crossing charged particle track to the upstream and downstream PMTs.

References

[1] D.S. Carman *et al.*, *"The CLAS12 Central Time-of-Flight System"*, Nucl. Inst. and Meth. A **960**, 163626 (2020).

[2] D.S. Carman, *"Central Time-of-Flight Calibration Constants"*,
`https://www.jlab.org/Hall-B/ctof/notes/ctof_db.pdf`.

[3] D.S. Carman, *Tutorial for CLAS12 Central Time-of-Flight System Energy and Timing Calibrations*,
`https://www.jlab.org/Hall-B/ctof/calib/ctof_tutorial.pdf`.