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

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Abstract

This document details the algorithms for the 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 consists of 48 scintillation bars with double-ended readout that form a hermetic barrel surrounding the target and inside the 5-T superconducting solenoid magnet. A detailed description of the CTOF system is provided in Ref. [1]. There are two parts of the system calibration. The first employs cosmic ray data or minimum-ionizing particle beam data acquired using a Central Detector trigger to gain match the system PMTs. This portion of the calibration uses the ADC information for the upstream and downstream PMTs of each counter and the output of the calibration is a set of PMT high voltage settings. The reconstruction code also uses this calibration information to compute the energy deposited in each bar for passing charged particles. The second part of the calibration employs beam data to determine the system parameters to optimize the counter timing resolution for charged particles. This portion of the calibration is a multi-step process that must be completed in a specific order. Both types of calibrations typically require several iterations to converge to the optimal parameter settings. 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 CTOF counter. These parameters are:

- *mipa* - Fit centroid of the Landau peak in the ADC geometric mean histogram for minimum ionizing particles
- *mipa_err* - Uncertainty in the fit of the Landau peak 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, *mipa_upstream* and *mipa_downstream* are filled with the same fit centroid for the minimum ionizing peak for the geometric mean ADC distribution. The gain balancing parameters also include the uncertainties in the determination of the geometric mean (*mipa_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 FTOF counter in units of ADC channels. In sorting the ADC geometric mean distributions for each counter, no data selection criteria are applied beyond the trigger condition, as the triggering particles are nearly all minimum ionizing particles in the nominal cosmic ray or beam data runs used to determine the PMT high voltage settings. 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.

The algorithm fits the geometric mean spectrum for each counter with a composite function of a Landau signal and an exponential background. Fig. 1(left) shows an ADC geometric mean plot for one representative FTOF counter with the fit functional overlaid.

2.2 ADC Logarithm Ratio

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

$$\mathcal{R} = \log\left(\frac{ADC_D - PED_D}{ADC_U - PED_U}\right). \tag{2}$$

In forming the ADC log ratio (see Fig. 1(right)), again event selection is not necessary beyond the trigger condition and a minimum $\overline{ADC}$ cut (500). The algorithm fills a histogram with the logarithm of the ADC ratio. The mean (*logratio*) and its uncertainty (*logratio_err*) are the returned values.

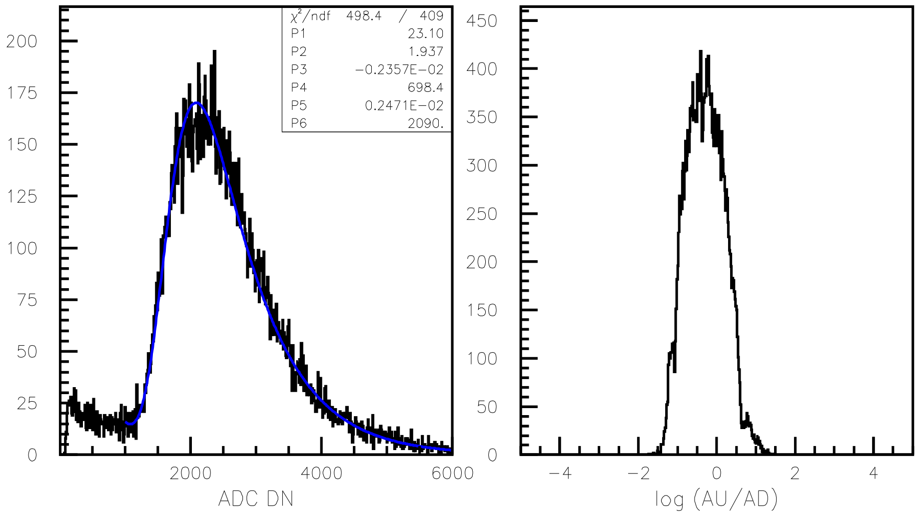

Figure 1: (Left) ADC geometric mean distribution with the fit result overlaid and (right) ADC log ratio distribution for one representative CTOF counter.

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 using the algorithm described in Ref. [3].

In short, 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:

$$G_U = \frac{\overline{ADC}}{\sqrt{\exp \mathcal{R}}}, \qquad G_D = \overline{ADC} \cdot \sqrt{\exp \mathcal{R}}. \tag{3}$$

The next step is to compute the required high voltage values using:

$$\Delta V_{U,D} = \frac{V_{U,D}^{orig} \cdot (ADC_{MIP} - G_{U,D})}{G_{U,D} \cdot \alpha}, \tag{4}$$

$$V_{U,D}^{new} = V_{U,D}^{orig} + \Delta V_{U,D}, \tag{5}$$

where ADC_{MIP} is the desired channel for the minimum ionizing peak centroid in the $\overline{ADC}$ spectrum (2000), 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 sets $|\Delta V| = 250$ V if $|\Delta V| > 250$ 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 counter energy loss for the passing charged particles is determined from the gain balancing calibration parameters in the FTOF reconstruction code. The following steps are used to determine the energy loss:

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

  $$\mathcal{K} = \left[\frac{\left(\frac{dE}{dx}\right)_{MIP} \cdot t}{ADC_{MIP}} \right], \tag{6}$$

  where ADC_{MIP} is the nominal 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 as:

  $$E_{U,D} = G_{U,D} \cdot \mathcal{K}, \tag{7}$$

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

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

  $$E^{corr}_{U,D} = E_{U,D} \exp\left(\frac{d_{U,D}}{\lambda}\right), \tag{8}$$

  where $d_{U,D}$ are the distances along the bar from the track hit position to the upstream and downstream PMTs (see Eq.(19) in Appendix A for definitions) and λ is the counter attenuation length determined using the algorithm `ATTEN` in Section 3.2.

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

  $$E_{dep} = \sqrt{E^{corr}_{U} \cdot E^{corr}_{D}}. \tag{9}$$

3 Timing Calibration

The timing calibration constants for the CTOF system are determined in a specific sequence. The steps are given 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, `RFP` and `RFS` for the radio-frequency offset determinations, and `P2P` for the counter-to-counter timing offset determination.

Step #	Calibration	Algorithm
1	Upstream-Downstream PMT Timing Alignment	`UD`
2	Attenuation Length	`ATTEN`
3	Effective Velocity	`VEFF`
4	Counter RF Offset	`RFP`
5	Paddle to Paddle Delays	`P2P`
6	System RF Offset	`RFS`

Table 1: The steps and their order for the CTOF timing calibrations.

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 determines this timing offset from the mean of the time difference histogram. Event selection is not needed other than the trigger condition. The database parameter is:

- *upstream_downstream* - upstream/downstream PMT TDC time difference (ns) for each counter,

The algorithm needs the TDC values from both ends of each counter. The expected distribution is a plateau with two sharp edges as shown in Fig. 2. 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.(18).

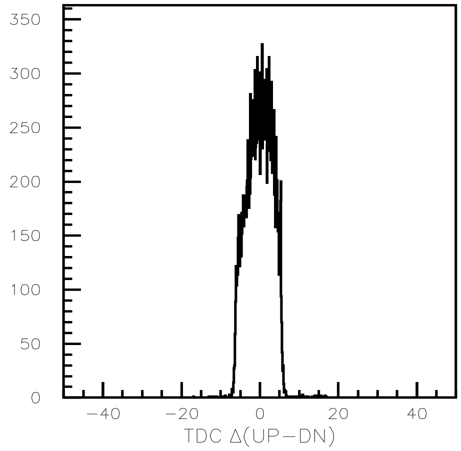

Figure 2: Representative upstream-downstream PMT TDC time difference distribution (ns) for one representative CTOF counter.

3.2 Attenuation Length

The attenuation length calibration algorithm `ATTEN` is used to account for the energy attenuation 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* - measured attenuation length (cm) for each end of each counter
- *attlen_err* - uncertainty of the measured attenuation length (cm)
- *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 vs. coordinate (see Fig. 3) of the form:

$$\log\left(\frac{ADC_D - PED_D}{ADC_U - PED_U}\right) = y\_offset + \frac{2 \cdot coor}{attlen}, \tag{10}$$

where *y_offset* (a constant) is the y-intercept and $attlen = 2/\text{slope}$. The parameter *attlen_err* is the fit uncertainty associated with the attenuation length fit. No uncertainty for the y-intercept parameter is stored. 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:

$$coor = (t_U - t_D) \cdot \frac{v_{eff}}{2}, \tag{11}$$

where v_{eff} is the counter effective velocity determined using the algorithm `VEFF` described in Section 3.3. For the initial attenuation length estimation, v_{eff} is set to 16 cm/ns.

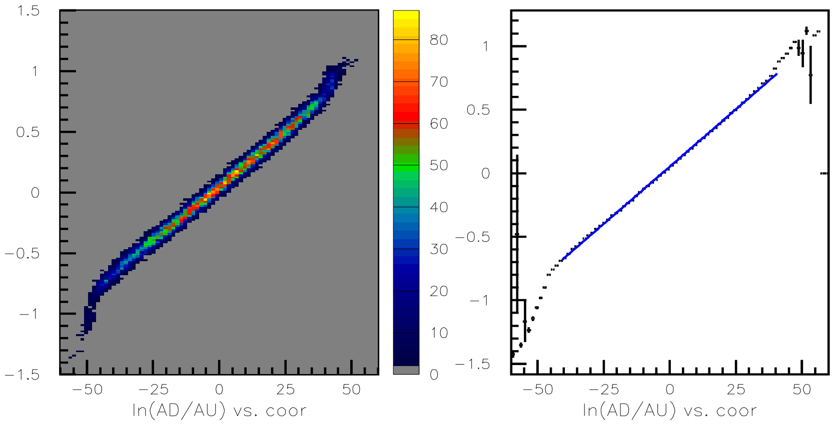

Figure 3: Plot of the ADC log ratio vs. reconstructed hit coordinate (cm) from the PMT hit times and the corresponding fit for a representative CTOF counter.

3.3 Effective Velocity

The effective velocity is the 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:

- *veff* - effective velocity of the counter for each end (cm/ns)
- *veff_err* - uncertainty in the determined 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.(11):

$$coor_{DC} = (t_U - t_D) \cdot \frac{v_{eff}}{2}. \tag{12}$$

Here the CTOF hit coordinate along the counter is now determined independently from the Central Vertex Tracker (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 *veff* assuming *veff_upstream* = *veff_downstream*.

Fig. 4 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 Central Vertex Tracker 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. 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.

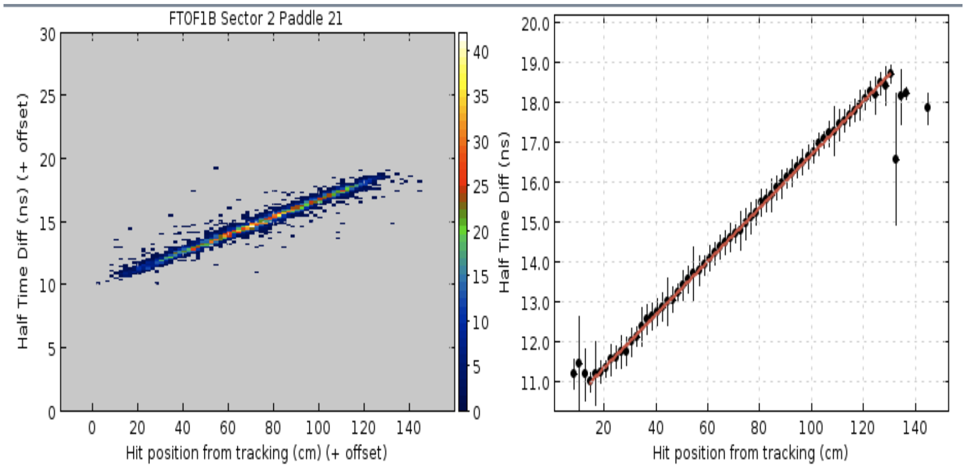

Figure 4: Distribution of half the upstream/downstream TDC time difference versus the coordinate along the counter $coor_{CVT}$ from Central Vertex Tracker tracking information and the corresponding fit for a representative CTOF counter.

3.4 Paddle RF Offset Calibration

To determine the flight time of charged particles from the target vertex to each counter of the CTOF system, the event start time needs to be synchronized to the accelerator RF time as the beam interacts with the target coincident with an RF bucket. The beam bunch width within the RF beam bucket is only ∼2 ps and, therefore, represents a precise time marker. In theory then the RF time serves as the event start time. In practice, however, as the RF time signal has a period of T_{RF}, it is not initially known which RF beam bucket was the one associated with the event that led to the hits in the CTOF counters.

The synchronization of the event start time with the RF time is performed in two stages. In the first stage, using the `RFP` algorithm, time offsets are determined for each CTOF counter relating the vertex time to the RF time. In the second stage, after the `P2P` algorithm is used to fix the specific RF beam bucket associated with the event, the RF offsets are checked for the FTOF system as a whole using the algorithm `RFS`. This procedure is followed as there may be an overall shift in the relative RF timing due a change in the accelerator setup that can be handled through the `RFS` algorithm leaving the counter-specific RF offsets that were determined through the `RFP` algorithm unchanged.

The algorithm `RFP` is carried out selecting pions. The difference between the event start time and the RF time is given by:

$$\Delta RF = t_{RF} - \left(\bar{t}_\pi - \frac{L_\pi}{\beta_\pi} + \frac{z_{vert}}{\beta_\pi}\right), \tag{13}$$

where t_{RF} is the RF time, $\bar{t}_\pi$ is the measured pion hit time in the CTOF counter, L_π is the measured path length of the pion track from the vertex to the CTOF counter from the Central Vertex Tracker tracking information, β_π is the pion velocity, and z_{vert} is the z-coordinate of the event vertex position from Central Vertex Tracker tracking information.

In the expression of ΔRF in Eq.(13) there are three relevant terms:

- t_{RF} - the RF time
- $(\bar{t}_\pi - L_\pi/\beta_\pi)$ - the event start time with $\bar{t}$ defined by Eq.(21) in Appendix A.
- z_{vert}/β_π - vertex correction time to compensate for the effect of target length

The purpose of the RF calibration is to fix the mean value of ΔRF to zero for each CTOF counter to eliminate any dependence of ΔRF on the RF time. Proper calibration of the RF timing ensures an accurate determination of the track timing parameters. The value of the offset should be within the width of a beam bucket T_{RF}.

The counter RF offsets are determined using the modulus of ΔRF with T_{RF}. However, as the ΔRF distribution can wrap around the T_{RF} time window, a procedure has been implemented to "unfold" this wrap-around effect. The peak channel in the ΔRF distribution is found, ΔRF_P. The portion of the distribution to shift to remove the wrap-around is handled using the following adjustments: If $\Delta RF > \Delta RF_P - 0.5T_{RF}$, then $\Delta RF = -\Delta RF$ or if $\Delta RF < \Delta RF_P - 0.5T_{RF}$, then $\Delta RF = -\Delta RF$. Fig. 5(top) shows an example of the RF offset calibration for one representative counter. The top left plot shows the distribution of ΔRF wrapping around the T_{RF} window and the top right plot shows the distribution after

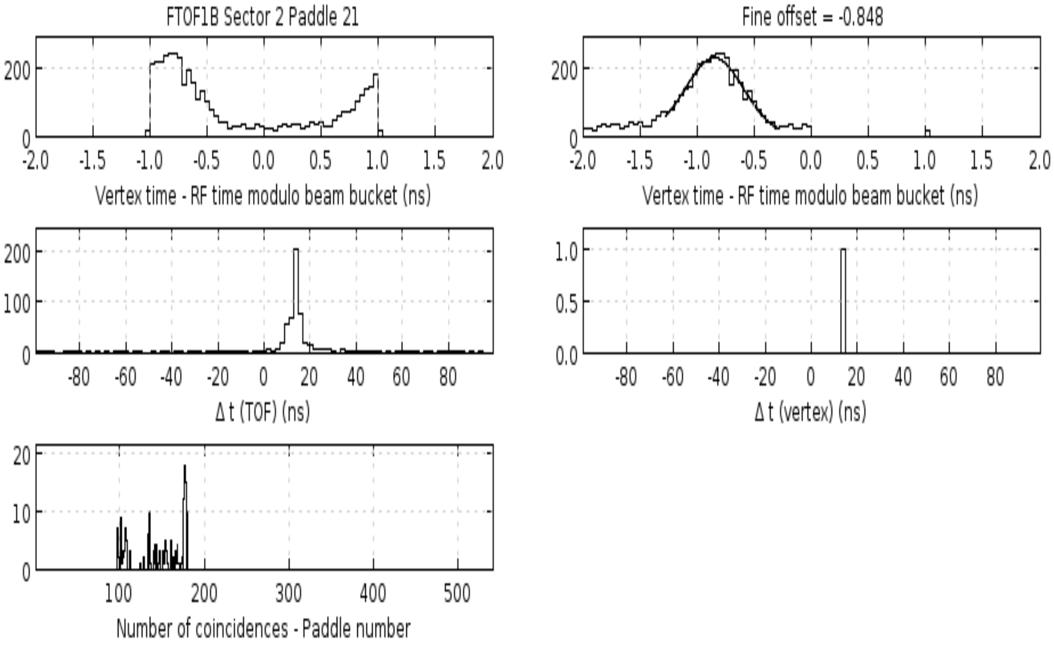

Figure 5: Distributions of unshifted and shifted ΔRF distributions (top), and the paddle-to-paddle time offsets (middle). The bottom plot shows the number of CTOF hit coincidences for each paddle in the system with the electron in the reference counter.

the adjustment of the ΔRF distribution. This modified distribution is fit with a Gaussian to determine the RF offset for each counter.

For both RF offset algorithms, `RFP` and `RFS`, the ΔRF histogram should be defined with a 25 ps bin size consistent with the LSB time resolution of the CTOF high resolution TDCs. To carry out this part of the calibration the timing corrections for the algorithm `UD` must be completed first and the determined parameters must be used to correct the recorded PMT TDC times.

3.5 P2P Calibration

After the RF offset calibration described in Section 3.4, the counter timing is precisely aligned modulo T_{RF}. The next step in the CTOF timing calibration is to fix the measured hit times for all counters to the specific RF bunch associated with the event. This is carried out using coincidences of charged tracks to link the hit times of all counters across the full CTOF system.

Events of the topology $ep \rightarrow e'\pi^{\pm}X$ are used to fix the time delays between the 48 CTOF counters that are aligned after the `RFP` calibration to within a multiple of T_{RF} to each other. For the `P2P` algorithm the database parameter is:

- *paddle2paddle* - counter to counter time-offset relative to the RF

The time offset parameter *paddle2paddle* is a single parameter for each counter that is restricted to values of $n \cdot T_{RF}$, with $n = 0, \pm1, \pm2, ...$ At the start of the `P2P` calibration, all offset values are set to zero. The following sequence is used to complete the calibration:

1). From the sample of all exclusive $ep \to e'\pi^+X$ and $ep \to e'\pi^-X$ events, select events with good electron and good $\pi^\pm$ particle identification. Select tracks with $p > 1$ GeV to reduce issues with energy loss and/or multiple scattering.

2). For each event compute the electron and pion vertex times TV for all hit counters. These vertex times are computed as:

$$TV^e_{S_e,C_e} = t_e - L_e/\beta_e, \tag{14}$$
$$TV^\pi_{S_\pi,C_\pi} = t_\pi - L_\pi/\beta_\pi, \tag{15}$$

where t_e and t_π are the CTOF counter hit times as defined in the Appendix A. Note that target length correction terms of the form z/β are not required here as the `P2P` calibration is based on using the $e\pi$ vertex time differences, and these terms would cancel out.

3). Choose a single reference counter pair for the electron and pion (*e.g.* S_e, C_e=1,10 = ref_e for the electron, S_π, C_π=4,10 = ref_π for the pion) and compute the reference vertex time difference $TV^{e\pi}_{ref_e,ref_\pi}$ for this pair:

$$\begin{aligned} TV^{e\pi}_{S_e,C_e,S_\pi,C_\pi} &= TV^e_{S_e,C_e} - TV^\pi_{S_\pi,C_\pi} \\ &= TV^{e\pi}_{1,10,4,10} \\ &= TV^{e\pi}_{ref_e,ref_\pi}. \end{aligned} \tag{16}$$

4). Define the vertex time differences between the reference counter pair and all other counter pairs always with the same electron reference counter as:

$$\Delta TV = TV^{e\pi}_{ref_e,ref_\pi} - TV^{e\pi}_{ref_e,S_\pi,C_\pi}. \tag{17}$$

This vertex time difference should be computed 540 times for all counters in the FTOF system relative to the reference time TV. The `P2P` correction for each counter (S_π, C_π) is determined from Eq.(17) by selecting the time value of the bin with the maximum bin content, with the histogram binning in T_{RF}. Note that in Eq.(17) the electron timing effectively drops out and ΔTV compares pion timing between all counter pairs.

Fig. 5(middle) shows an example of the `P2P` calibration for one representative counter. The middle left plot shows the FTOF time hit time difference for the selected e/π event and the middle right plot shows the associated vertex time difference. Note that to carry out this part of the calibration the timing corrections for the algorithms `UD` and `RFP` must be completed first and the determined parameters must be used to correct the recorded PMT TDC times.

3.6 System RF Offset Calibration

The final step in the CTOF timing calibration is to check the RF time offset for the full CTOF system. This step of the calibration is referred to as `RFS` and is meant only to determine if there is an overall shift in the relative RF timing due to changes in the accelerator setup. In such a situation a single RF offset applied to all counters in the CTOF system is performed. The procedure is identical to that described in Section 3.4, but not the RF Offset from Eq.(13) is checked by summing the over all counters the vertex time difference relative to the RF in a histogram defined with a 25 ps bin size.

To carry out this part of the calibration the timing corrections for the algorithms `UD`, `RFP`, and `P2P` must be completed first and the determined parameters must be used to correct the recorded PMT TDC times.

4 CTOF Calibration Approach

The timing calibration is an iterative procedure that is completed using CVT tracking for each iteration.

After the multiple iterations through 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:

$$\begin{aligned} t_U &= (\mathcal{C}_{TDC} \cdot TDC_U) - \frac{\mathcal{C}_{UD}}{2} + t_{RF}^{pad} + \mathcal{C}_{p2p} + t_{RF}^{sys}, \\ t_D &= (\mathcal{C}_{TDC} \cdot TDC_D) + \frac{\mathcal{C}_{UD}}{2} + t_{RF}^{pad} + \mathcal{C}_{p2p} + t_{RF}^{sys}, \end{aligned} \tag{18}$$

where $\mathcal{C}_{TDC}$ is the TDC conversion time ($\sim$24 ps/channel), TDC is the measured TDC channel, $\mathcal{C}_{UD}$ is the time shift determined from the `UD` algorithm, t_{RF}^{pad} and t_{RF}^{sys} are the paddle-specific and system RF timing offsets determined from the algorithms `RFP` and `RFS`, respectively, and $\mathcal{C}_{p2p}$ is the time shift determined from the `P2P` algorithm.

Fig. 6 provides a flowchart of the CTOF timing calibration sequence detailing the ordering of the individual steps and what calibration parameters are used at each step and which are passed from previous steps in the calibration. The parameters used as input for the different calibration steps for each iteration are detailed in Tables 2, 3, and 4.

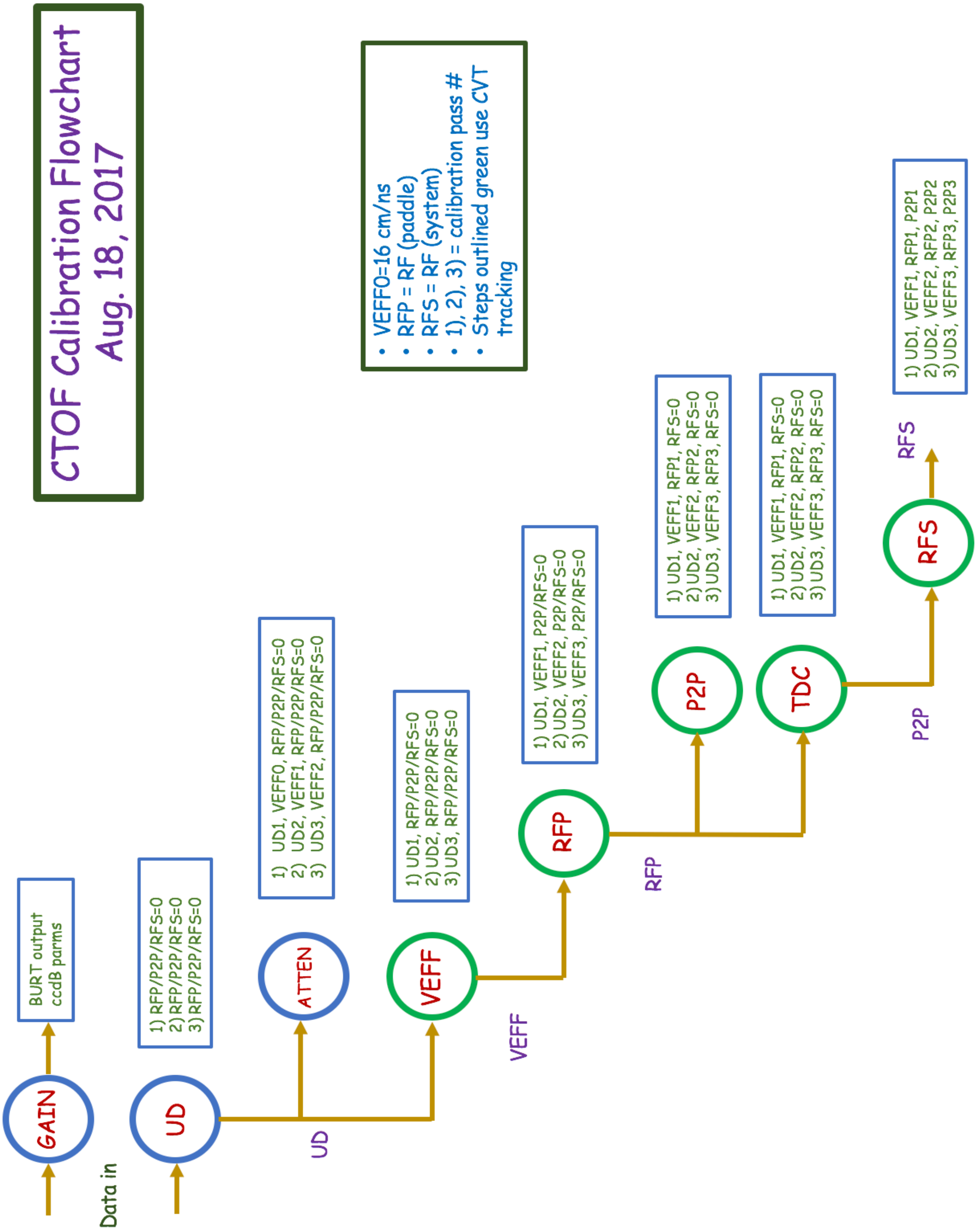

Figure 6: Flowchart detailing the ordering of the CTOF calibration procedure and the parameters that are passed from step to step.

CTOF Timing Calibration - Iteration #1		
Calibration	Input Parameters	Output Parameters
UD	(RFP,P2P,RFS)=0	UD1
ATTEN	UD1, VEFF0, (RFP,P2P,RFS)=0	ATTEN1
VEFF	UD1, (RFP,P2P,RFS)=0	VEFF1
RFP	UD1, VEFF1, (P2P,RFS)=0	RFP1
P2P	UD1, VEFF1, RFP1, RFS=0	P2P1
RFS	UD1, VEFF1, RFP1, P2P1	RFS1

Table 2: The input and output parameters for each of the CTOF timing calibration algorithms. This table reflects the requirements for the first iteration of the calibration. Note 1) all tracking information comes from the CVT, 2). VEFF0=16 cm/ns, 3). Input quantities listed as =0 are parameters whose values are set to 0 for the calibration step.

CTOF Timing Calibration - Iteration #2		
Calibration	Input Parameters	Output Parameters
UD	(RFP,P2P,RFS)=0	UD2
ATTEN	UD2, VEFF1, (RFP,P2P,RFS)=0	ATTEN2
VEFF	UD2, (RFP,P2P,RFS)=0	VEFF2
RFP	UD2, VEFF2, (P2P,RFS)=0	RFP2
P2P	UD2, VEFF2, RFP2, RFS=0	P2P2
RFS	UD2, VEFF2, RFP2, P2P2	RFS2

Table 3: The input and output parameters for each of the CTOF timing calibration algorithms. This table reflects the requirements for the second iteration of the calibration. Note 1) all tracking information comes from the CVT, 2). Input quantities listed as =0 are parameters whose values are set to 0 for the calibration step.

CTOF Timing Calibration - Iteration #3		
Calibration	Input Parameters	Output Parameters
UD	(RFP,P2P,RFS)=0	UD3
ATTEN	UD3, VEFF2, (RFP,P2P,RFS)=0	ATTEN3
VEFF	UD3, (RFP,P2P,RFS)=0	VEFF3
RFP	UD3, VEFF3, (P2P,RFS)=0	RFP3
P2P	UD3, VEFF3, RFP3, RFS=0	P2P3
RFS	UD3, VEFF3, RFP3, P2P3	RFS3

Table 4: The input and output parameters for each of the CTOF timing calibration algorithms. This table reflects the requirements for the third iteration of the calibration. Note 1) all tracking information comes from the CVT, 2). Input quantities listed as =0 are parameters whose values are set to 0 for the calibration step.

A CTOF Hit Coordinate Determination

Fig. 7 shows a representation of an 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:

$$d_U = \left(\frac{C_L}{2} + coor\right), \qquad d_D = \left(\frac{C_L}{2} - coor\right). \tag{19}$$

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

$$t^U_{hit} = t_U - \frac{d_U}{v_{eff}}, \qquad t^D_{hit} = t_D - \frac{d_D}{v_{eff}}. \tag{20}$$

The average hit time is then given by:

$$\begin{aligned} \bar{t}_{hit} &= \frac{1}{2}(t^U_{hit} + t^D_{hit}) \\ &= \frac{1}{2}\left[t_U - \left(\frac{C_L}{2} + coor\right)\frac{1}{v_{eff}} + t_D - \left(\frac{C_L}{2} - coor\right)\frac{1}{v_{eff}}\right] \\ &= \frac{1}{2}\left[t_U + t_D - \frac{L}{v_{eff}}\right]. \end{aligned} \tag{21}$$

The hit coordinate along the bar is given by:

$$coor = \frac{v_{eff}}{2}(t_U - t_D - upstream\_downstream), \tag{22}$$

where *upstream_downstream* is the left-right timing alignment parameter defined in Section 3.1.

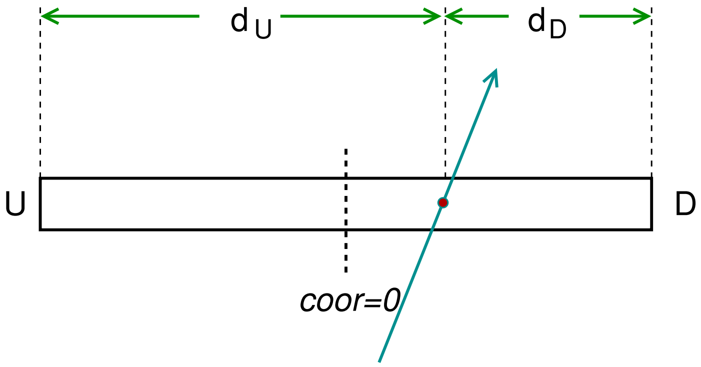

Figure 7: Definition of the hit distances d_U and d_D from the hit position of the crossing charged particle track to the upstream and downstream PMTs.

References

[1] D.S. Carman, *"Central Time-of-Flight Geometry for CLAS12"*, CLAS12-Note 2014-005.

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

[3] D.S. Carman, *"CTOF Bench Testing Results"* - CLAS12-Note 2016-009.