Signal processing techniques for precise timing with novel gaseous detectors

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Abstract. The experimental requirements in current and near-future accelerators and experiments have stimulated intense interest in R&D of detectors with high precision timing capabilities, resulting in novel instrumentation. During the R&D phase, the timing information is usually extracted from the signal using the full waveform collected with fast oscilloscopes; this method produces a large amount of data and it becomes impractical when the detector has many channels. Towards practical applications, the data acquisition should be undertaken by dedicated front-end electronic units. The selected technology should retain the signal timing characteristics and consequently the timing resolution on the particle’s arrival time.

We investigate the adequacy of the Leading-edge discrimination timing technique to achieve timing with a precision in the order of tens of picoseconds with novel gaseous detectors. The method under investigation introduces a “time-walk” which impinges on the timing resolution. We mitigate the effect of time-walk using three different approaches; the first based on multiple Time-over-Threshold, the second based on multiple Charge-over-Threshold information and the third uses artificial Neural Network techniques. The results of this study prove the feasibility of the methods and their ability to achieve a timing resolution comparable to that obtained using the full waveforms.

1. Introduction

Fast timing capabilities have been appointed as an important parameter in the effort to resolve extremely large event multiplicities on particle detection systems. In order to mitigate the pile-up using Time-of-Flight measurements in extended systems, detectors with a timing resolution in the order of tens of picoseconds are required. Such instrumentation has been developed using gaseous detectors, specifically the PICOSEC Micromegas [1], which during the R&D phase proved the ability to time Minimum Ionising Particles (MIP) with a precision of 24 ps. Usually, the timing information is extracted with the Constant Fraction Discrimination (CFD) method that requires the full digitised waveform. Nevertheless, acquisition of the full waveform in each detection device would require a complicated Data Acquisition (DAQ) system. It is desirable that the front-end electronics of such a detector provide the required experimental information for precise timing with the minimum possible data transfer rate and power consumption.

In this work we investigate the adequacy of a Leading-edge timing method by applying signal processing techniques on data collected by the PICOSEC Micromegas detector on 150 MeV muon beam [2]. In this technique, the Signal Arrival Time (SAT) is determined when the leading edge
of the signal crosses a threshold at a fixed amplitude. Although this timing measurement suffers from time-walk, we show that this systematic error can be corrected, resulting to a very precise timing measurement.

It is well known that such a timing correction relies on the knowledge of the pulse size (e.g. peak amplitude or pulse integral). Usually Time-over-Threshold (ToT) measurements are employed to estimate the pulse size. However, such timing corrections based on a single ToT measurement are not adequate. This is due to the fact that the ToT value does not provide a precise estimation of the pulse amplitude and also this precision depends on the pulse height. To mitigate this problem we time the arrival of the signal at three different pulse amplitude thresholds and in addition we use the respective ToT information to correct for time-walk (hereafter we refer to this technique as “multi Time-over-Threshold”, multi-ToT).

Alternatively, we have investigated another way to correct for time-walk, which, instead of ToT, uses the integral of the pulse (i.e. the charge) above a fixed threshold (hereafter called “Charge-over-Threshold”, CoT, method). The Charge-over-Threshold method provides a better estimation of the pulse size than the ToT method, because it is almost insensitive on the pulse fluctuations near the threshold. This work shows that by using multiple thresholds to time the pulse and by employing the respective Charge-over-Threshold values to correct for time-walk, we can achieve timing results with the same precision as those obtained by applying the CFD method on the whole waveform. These timing techniques can be easily realised in front-end electronics by using existing very precise constant threshold timing electronics (e.g. NINO chip [3]) and by integrating the pulse over threshold by a single ADC. Additionally, due to the fact that we need limited amount of experimental information (3 threshold crossings and the respective ADC measurements) we can envisage online precise estimation of the SAT using artificial Neural Networks.

This article is organised as follows: Section 2, after a brief description of the CFD method, describes the application and performance of the multi-ToT method. Section 3 discusses the application and results of the multi-CoT technique, whilst the implementation of the above techniques using artificial Neural Networks is presented in Section 4. Finally a comparison between the methods and concluding remarks are presented in Section 5.

2. CFD Timing and multi-ToT approach

In this work, we use experimental data collected by the CERN-RD51 PICOSEC Micromegas collaboration in 150 GeV muons at the CERN SPS H4 secondary beam-line using a multipad PICOSEC Micromegas detector. The analysis of these waveforms based on the CFD technique (timing the arrival of the pulse when it reaches 20% of its amplitude) has been published in [2]. In the present work, a 50.5 ps timing resolution has been measured for all tracks passing through a single pad (pads are hexagonal with a diameter of 1 cm). When the track passes within 2 mm from the center of the pad, the timing resolution has been measured to be 26.5 ps, in agreement with the aforementioned publication [2].

In this section we report the performance of the multi-ToT technique applied on the same waveforms. The ToT method takes advantage of the fact that the shape of the pulses is, to some extent, predictable: the pulses can be approximated as standard shape curves or a superposition of many such curves, according to the number of electrons on the anode (sensor) of a gaseous detector. Thus, a time-based technique which uses a digitized information of the input signal can be realized by shifting the focus, from the full waveform to just how long a given pulse remains above a (user-predetermined) voltage threshold; all the important characteristics of the shape are subsequently inferred from the Time-over-Threshold information. A defect of this method is that is suffers from a poor linearity between the ToT value and the pulse amplitude, where a much higher slope is observed at high ToT values. For a 10 mV threshold, this relation is shown in Figure 1 (left, black points), where, for pulses with amplitudes up to ≈50 mV, the
ToT value has a low sensitivity in estimating the pulse amplitude (a change in the ToT value describes a relatively small change on the pulse amplitude). However, beyond this point a small change in the ToT value yields a large change in the pulse amplitude, resulting in an imprecise pulse amplitude prediction. The accuracy of this prediction affects the precision of the time-walk correction and finally the timing resolution. Similar problems are observed in the ToT vs. pulse amplitude relation when other thresholds are used; in Figure 1 (left), the red points refer to a threshold of 50 mV, while the green points refer to a threshold of 100 mV.

For this reason, the use of multiple constant thresholds is proposed. After examining several different algorithms, we concluded on the use of 3 constant thresholds, as illustrated in Figure 1 (right); for the data set we use, these thresholds are defined at 10, 50 and 100 mV.

The selection of these specific constant thresholds for the dataset at hand, is justified by Figure 2 (left), where the black solid circles present the timing resolution as a function of the pulse amplitude obtained by the CFD timing method, while in red open circles, green squares and blue triangles present the timing resolution as a function of the pulse amplitude obtained by the Leading edge timing method and a time-walk correction with the single ToT method using 10, 50 and 100 mV constant threshold respectively. As seen in this Figure, the time resolution improves with the pulse amplitude. But, each individual threshold is not applicable to all pulses, since some of them have a lower amplitude than the threshold. Nevertheless, a resolution comparable to the one obtained by the CFD method can be achieved over the whole range of pulses, by using the highest among the 3 thresholds available on an event per event basis. For each of these thresholds, a parameterisation of SAT as a function of ToT has been implemented with the use of a 4th order polynomial, aiming to correct for the time-walk effect. An example of this parameterisation is presented in Figure 2 (right) for the 10 mV threshold.

Making use of the 3 thresholds and the respective ToT values as explained above, we obtain the SAT from the highest available threshold and we correct this SAT value for the time-walk on an event by event basis, using the respective ToT value and the parametrised functions shown in Figures 2 (right) and 3. The resulting SAT distribution from this method is shown in Figure 4 (left) for the full data set, and (right) for events where the signal is fully contained in a single pad; the time resolution, obtained as in Reference [1], is found to be 48.8 ps and 28.2 ps, respectively.
Figure 2. (Left) Compilation of timing resolution as a function of the pulse amplitude using the CFD timing technique (black solid circles), and the Leading-edge timing method corrected for time-walk using the ToT method at a constant threshold of 10 mV (red open circles), 50 mV (green squares) and 100 mV (blue triangles). (Right) The Signal Arrival Time as a function of ToT, parameterised by a 4th order polynomial for the case of the 10 mV threshold.

Figure 3. Same as in the right part of Figure 2, but for a threshold of 50 mV (Left), and a threshold of 100 mV (Right).

3. Timing with the multi Charge-over-Threshold method
In this Section, we investigate a method which, instead of the time that the pulse remains above the threshold, makes use of the charge (i.e. the area of the pulse) above the threshold, as illustrated in Figure 5 (left).

The multi Charge-over-Threshold is used to derive the time-walk correction on an event by event basis, in analogy with the multi-ToT method described above. The time-walk is directly related with the pulse size and the charge over the threshold gives an accurate estimate of this size. Since the pulse amplitude and charge are closely related, one could have derived a time-walk correction using the amplitude of each pulse. Nevertheless, using the amplitude is not as
Figure 4. (Left) Signal arrival time after time-walk correction with the multi ToT technique. Making use of the highest available voltage threshold, a 48.8 ps timing resolution is obtained for the full data set. (Right) SAT distribution for events where the signal is fully contained in a single pad in the detector area obtain a 28.2 ps timing resolution.

Figure 5. (Left) Demonstration of the Charge-over-Threshold method. The area of the pulse above the threshold (blue area) is used for the parameterisation of the time-walk correction. (Right) SAT as a function of the Charge above a 10 mV threshold. The dependence is parameterised by a power law and is used for the time-walk correction.

robust as using the charge, because all the superimposed pulses that form the signal have a linear contribution to the pulse charge, while possible delays in the signal formation may distort the pulse maximum amplitude. Moreover, as mentioned earlier, the use of the pulse charge above a threshold avoids near-baseline fluctuations of the pulse.

Figure 5 (right) presents the SAT as a function of the charge above the threshold for a 10 mV constant threshold. This functional form of this dependence is described by a power law plus a constant factor for all the used thresholds (10, 50, 100 mV), as shown also in Figure 6; as in the multi-ToT method described in the previous Section, the corresponding parameterisation from
Figure 6. Same as in the right part of Figure 5, but for a threshold of 50 mV (Left), and a threshold of 100 mV (Right).

the higher available threshold is used for the correction of the time-walk effect.

Figure 7. Compilation of the timing resolution as a function of the total pulse charge using the CFD timing technique (black solid circles), and Charge-over-Threshold method at 10 mV (red open circles), 50 mV (green squares) and 100 mV (blue triangles) constant threshold.

Figure 7 justifies the use of the highest available among the three selected thresholds. In this Figure, the timing resolution is shown as a function of the total charge of the pulse. The black solid circles correspond to the resolution obtained by the CFD timing technique. The colored circles correspond to the resolution obtained by using the three different constant thresholds (red-10 mV, green-50 mV and blue-100 mV) to estimate the SAT and to correct it for time-walk on an event-by-event basis with the corresponding CoT parameterization shown in Figures 5 (right) and 6. As seen in Figure 7, the time resolution of the CoT method is comparable to the this of the CFD method, when the CoT from the highest available threshold is used. In Figure 8 (left), the SAT distribution corrected for time-walk is shown for events where the signal is fully
Figure 8. SAT after time-walk correction with the Charge-over-Threshold technique, making use of the highest available voltage threshold. (Left) A 23.2 ps timing resolution is obtained for events where the signal is fully contained in a single pad in the detector area. (Right) SAT distribution for the full data set obtain a 44.9 ps timing resolution.

contained in a single pad; the obtained resolution is 23.2 ps, comparable to the demonstrated timing resolution from the PICOSEC collaboration [1]. Additionally, a 44.9 ps timing resolution is obtained for the full data set, shown in Figure 8 (right), which is slightly better compared to the 50.5 ps timing resolution that CFD method provides.

4. Timing with artificial Neural Network techniques
In addition to the analytical methods described earlier, we evaluate the use of artificial Neural Network techniques on the estimation of the time-walk correction. In this case, for each of the three predefined thresholds available per event, we provide as an input to the artificial Neural Network the timestamps determined by the Leading-edge method, and the corresponding ToT values.

Figure 9. The SAT as a function of the pulse amplitude after time-walk correction.

For the optimum performance of the network, we normalise each ToT value to the maximum ToT value observed in the data set. Since the target value of the SAT in each event is zero, the
network would always predict 0 whatever the input is. To avoid this, we add a random noise from a uniform distribution (-1,1) to the SAT inputs. For network training purposes we divide the full data set into 10 “folds” and we rotate the folds using each time 9 folds for training and 1 for validation. This way, we use 10 different networks to acquire the predictions for the whole data set. Moreover, for each fold, we enhance the data set, by using the same training data points many times ($\times 10$), with different random noise.

![Signal Arrival Time distribution](image1)

**Figure 10.** Signal Arrival Time distribution after time-walk correction using artificial Neural Networks techniques. (left) Events that the signal is fully contained in a single pad in the detector area obtain 24.4 ps time resolution. (Right) Timing resolution is obtained at 46.0 ps for the full data set. In both cases time resolution calculated as the weighted sum of two Gaussian functions.

The output of the network represents the time-walk correction on an event per event basis. Figure 9 presents the timing resolution as a function of the pulse amplitude. This Figure confirms the power law dependence of the timing resolution as a function of pulse amplitude that has been observed with analytical methods. The distribution of the SAT values (corrected for time-walk) for events where the signal is fully contained in a single pad is presented in Figure 10 (left) and the timing resolution is found to be 25.2 ps, which is a value similar to the analytical methods presented above. Figure 10 (right) presents the equivalent distribution for the whole data set; a time resolution of 46.0 ps is obtained in this case.

5. Conclusions

The adequacy of the Leading-edge timing method to provide the timestamp of a pulse was tested as an alternative to the CFD method for precise timing in tens of picosecond. The advantage of this method is that it requires minimal information from each pulse but, it suffers from an inherent time-walk effect. This problem was mitigated by using different approaches which have as a common characteristic the use of multiple thresholds. The multi Time-over-Threshold method provided a timing resolution similar to the CFD method applied on the full pulse waveform, while the multi Charge-over-Threshold method yields even better results; practical use of this last method relies on the condition that the Charge-over-Threshold information can be obtained with dedicated front-end electronics. Finally, preliminary results obtained with an artificial Neural Network are very promising and encourage further investigation of Neural Network techniques for precise timing.

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