Offline noise calibration of the CAEN V1742 ADCs at the PADME experiment

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Abstract. This work aims to provide robust methods for offline calibration of the noise floor for CAEN's V1742 sampling ADCs, used at the PADME experiment. It has been found that a part of the noise in the final signals originates from not fully equalized storage capacitor properties in the DRS4 chip, even after application of the CAEN's proprietary *drs4* calibration. Two approaches to offline equalization are discussed and finally two methods are proposed for obtaining the calibration data from random and physics trigger runs.

1. Introduction

The PADME experiment is dedicated to dark photon searches in the process of annihilation of accelerated positrons with electrons in a fixed target [1, 2]. For the digitization of $\mathcal{O}(1000)$ of analog channels at the experiment 29 CAEN V1742 ADC boards are in use. A custom made trigger distribution system is in charge of synchronizing all the 29 boards [3]. The design of the data acquisition system (DAQ) allows for complete offline analysis with no prior knowledge for the signals, as the entire ADC waveforms are stored.

The ADC board V1742 is equipped with 32 analog input channels, 2 trigger input channels and several extra interfaces: an optical connection for data transmission, common trigger I/Os that can handle differential or NIM signals and a number of extra general purpose LVDS inputs/outputs. The key element of the digitizer board is the DRS4 chip, which was developed at the Paul Scherrer Institut for the MEG experiment [4]. The DRS4 is a low-noise switching capacitor buffer, capable of sampling 9 channels with 1024 storage capacitors for each channel.

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The sampling rate of the DRS4 chip is limited to 5 GS/s. A noise level of 0.35 mV is achievable after an individual capacitor-offset calibration [5].

There is a drs4 calibration procedure implemented in the digitizer firmware, that is configurable through the CAENDigitizer library interface [5]. Although the impact of this procedure is very large, we found that there is room for an additional offline calibration. A further data correction can be applied to the data collected with the stock calibration table, loaded in the hardware. Even if it is clearly stated that DRS4 has a radiation hard design [5], the proposed method can also correct for hardware degradation of the electronics.

The majority of the detectors in the PADME experiment are scintillating detectors [3] and produce significant signals. So the effect of an improvement in the ADC noise level is expected to provide a relatively small impact on the overall energy resolution. On the other hand, the proposed calibration is expected to lead to better time resolution and improved double pulse separation.

2. Methods and Materials

For the analysis, two data sets of 2020 run were used, later in text referred to as *Physics* and *Random* runs, respectively. During the *Physics* run, all detectors were operational, a beam with energy 440 MeV and intensity 25 kPOT was delivered to the experiment, and the trigger signal was provided by the accelerator. During the *Random* run no beam was delivered, but the trigger source remained the same. This special condition is equivalent to a random trigger which makes this particular run suitable for noise floor studies. Only the first 5000 events were used for both runs.

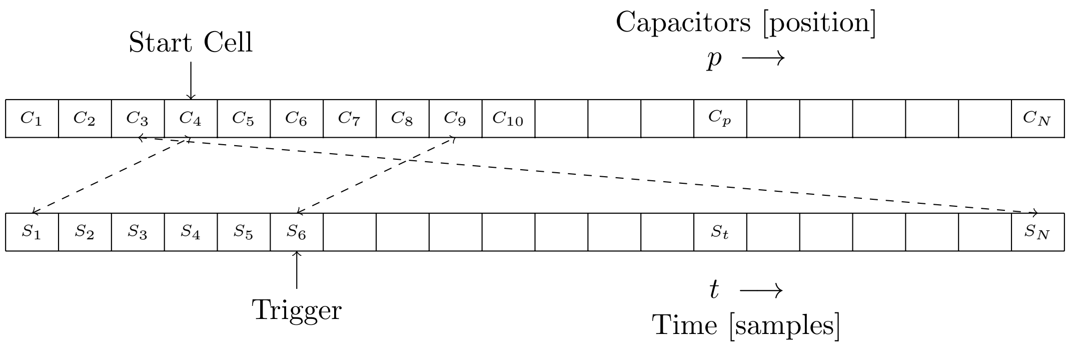

Figure 1. Illustration of the relationship between capacitors and time positions. The lower row represents samples S in time, while the upper one represents the capacitors in the circular buffer.

The data are organized in events. Each event contains information about the enabled ADCs, and their channels. 1024 amplitude samples are available per channel together with information about the starting position of the DRS4 circular buffer – $StartCell$. It is visible from figure 1 that the relationship between the time t and the capacitor position p is:

$$p = (t + StartCell) \bmod 1024 \tag{1}$$

As the triggers start the digitization process, they will appear almost at the same time on the waveform. In different events, the $StartCell$ may change leading to a different correspondence between the capacitor position in the circular buffer p and time step t. In order to calibrate the effects of inequalities of the capacitors it is not enough to subtract the pedestal for each time

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slot as multiple capacitors could be associated at a particular time slot. In accordance to the described model the calibration looks like:

$$S_{cor}(t) = S_{meas}(t) - E_{p(t)}(t), \tag{2}$$

where S_{meas} is the measured amplitude for a given time t, S_{cor} is its corrected value, $E_{p(t)}$ is the calibration function for the capacitor at position p at time t. Note the dependence on p of t (equation 1).

Different methods can be defined to obtain the calibration function $E_{p(t)}(t)$. Often, when access to raw data is needed, the researchers will need to run the reconstruction by their own, so the chosen strategy should satisfy these requirements: (i) the result should be obtained after a single pass over the data; (ii) the required computer resources should be compatible with a nowadays average computer; (iii) the method in any case should not worsen the noise condition.

In order to process the data on capacitor basis, the perspective should change from sequence of amplitudes ordered in time to sequence of amplitudes ordered by capacitor position using equation 1. Two main approaches were studied.

The first approach takes the mode of the amplitude distribution for each particular capacitor as a constant estimate of E_p. The method is realized by collecting per-capacitor histograms of the amplitudes for all the events in the data set. Once all events are processed, the value of the mode of the distribution can be determined.

The second approach accounts not only for the capacitor offsets but also for the time-dependent capacitor characteristics, for example parasitic currents charging or draining the storage capacitors. It relies on performing polynomial fits on amplitude distribution over time for each capacitor. Collecting per-capacitor 2D histograms for the amplitude values over time is not an option as it violates (ii) from the requirements list. In the present approach, the parameter's estimation is done by performing a χ^2 minimization procedure, based on the collection of a set of sums [6]:

$$a_{p,0} \cdots a_{p,k} = \arg \min_{a_{p,0} \cdots a_{p,k}} \underbrace{\sum_{events} (S_p(t) - E_p(t))^2}_{\chi^2}, \tag{3}$$

where $a_{p,0} \cdots a_{p,k}$ are the polynomial parameters for capacitor p, t is the time position where the capacitor at position p appears to be for the current event, k is the degree of the polynomial and

$$E_p(t) = \sum_{i=0}^{k} a_{p,i}\, S(t)^k. \tag{4}$$

In order to calculate the polynomial parameters the following sums should be collected:

$$\Sigma_{x^i} = \sum_{events} t^i, \quad \forall i \in [0, 2\,k] \tag{5}$$

$$\Sigma_{x^i y} = \sum_{events} t^i\, S(t), \quad \forall i \in [0, k]. \tag{6}$$

For polynomials up to 5-th degree the total number of sums is 17: $\sum x^0, \cdots, \sum x^{10}$ and $\sum x^0 y, \cdots, \sum x^5 y$.

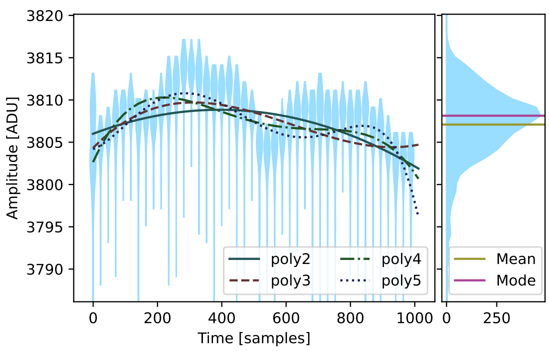
The source of floating point roundoff errors is eliminated by using integer variables for collecting the sums. By using 16 byte variables more than 10×10^8 events can be processed without overflow. This is well within the recommended limit for the number of events in a single run at the PADME experiment.

Both the statistical mode of the first approach and the a_0 of the polynomial approach are measures for the pedestal of the signals. In order to apply the corrections by preserving the initial offset, corrected offsets $o^{'}$ are to be calculated as:

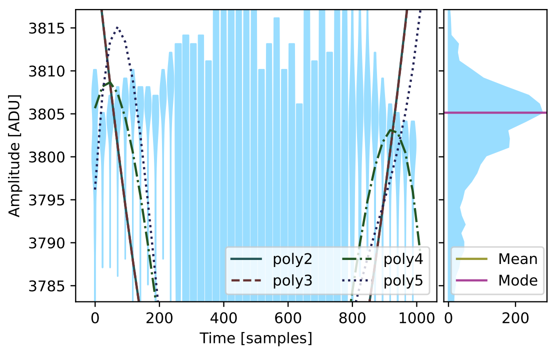
$$o_i^{'} = o_i - \frac{\sum_{j=1}^{1024} o_j}{1024}. \tag{7}$$

3. Results and Discussion

The time dependence of the amplitude for a single capacitor is shown on figure 2 as violin plots. The widths of the violins represent the occupancy at a given amplitude at a given time. Amplitude spectra are shown on right side of the figures. Figure 2a shows data from the *Random* run, while figure 2b shows data from the *Physics* run. These results are obtained in the same manner – the studied capacitor is №16 of channel 12 of ADC 27. This channel has been selected as it corresponds to a central crystal of the small angle electromagnetic calorimeter of PADME, that is exposed to the highest particle rate, so the effects of signal presence will be more pronounced.



(a) *Random* run



(b) *Physics* run

Figure 2. 5000 events ADC 27, channel 12, capacitor 16. The width of the violins represent the population at a given amplitude.

In figure 2a a reoccurring pattern is noticeable, which is an indication that such a calibration is applicable. Also it is visible that polynomials with higher degree approximate the data better. On the contrary figure 2b has a region with many signals starting at about $t = 250$ sample. All polynomials fit to the signals and failed to provide a measure for the noise floor. The mode of the amplitude distribution remained a good estimate of the offset of the capacitor.

Three combinations were tested:

(a) *Random* run with *Random* run calibration

(b) *Physics* run with *Random* run calibration

(c) *Physics* run with *Physics* run calibration

Results for (a) and (b) are provided in figure 3, where each violin shows the RMS of the noise distribution for all the channels with a given algorithm. Results for (c) are not shown on the figure as they copy the result for the mode in (b) and the results for polynomial calibration was worse than initial.

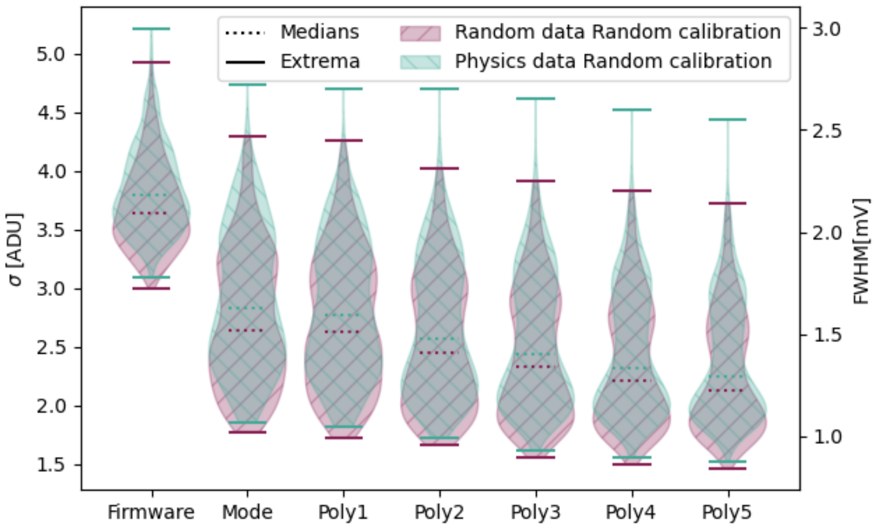


Figure 3. Comparison between different calibration methods. To obtain this plot 5000 events were used from both *Random* and *Physics* runs. Channels 16-24 of ADC27 are excluded from the statistics as they are known to be noisier.

The fact that the results from (a) and (b) are very close means that the pattern of capacitor inequalities is preserved over the time and it is possible to use calibration parameters obtained from different runs.

The structure in the shape of the violins corresponding to higher degree polynomials mean that there are other sources of noise which are individual to each particular channel and became dominant. So it will be very difficult to do any further improvement using these methods. The application of the algorithms shows significant improvement. A nearly two times better noise condition is achieved – starting at about 2 mV and getting lower than 1.2 mV in the case of Poly5 algorithm.

The suggestion is to use runs with *Cosmic* or *Random* triggers (or other runs with low counting rates) to calculate the calibration parameters with Poly5 method which can be used to calibrate *Physics* runs afterwards. If only runs with high counting rates are available, it is suggested to use the Mode method.

4. Conclusions

It has been found that CAEN's proprietary calibration, implemented in the firmware, does not produce the best possible noise condition and it can be further improved by running an offline calibration algorithm. Two main approaches to improve noise condition in the V1742 digitizers at PADME experiment were proposed and discussed. Such an improvement may lead to better time resolutions or easier peak separation.

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