Mitigating Dynamic Range Limitations in CHANDLER using Extrapolation

Janet Park[1]

[1] *University of Maryland, College Park*

August 2025

Abstract

The CHANDLER (Carbon Hydrogen Anti-Neutrino Detector with a Lithium Enhanced Raghavan optical lattice) detector is designed to measure neutrino signals, which vary according to a reactor's power and fuel composition. However, its data acquisition system has limitations due to the dynamic range of the analog-to-digital converter (ADC), making it susceptible to saturation. Large signals can cause waveform flattening, resulting in incomplete data. To address this, a system of photomultiplier tubes (PMTs) was studied–one with full exposure and one with partial exposure–using an LED flasher with varying DC voltages. A consistent ratio was found between the responses of the two PMTs within the unsaturated voltage range, which was used to scale the ADC counts within the dynamic range, resulting in expected values in the saturated voltage range. Using the saturated waveforms, the ends could be curve-fitted and used to extrapolate backward to recover the max ADC count for any saturated event. Comparing the extrapolated values to the expected, this method for recovering data from saturated waveforms was found to work most accurately at lower saturation-inducing LED intensities, but diverge from the expected at higher intensities. This study contributes to a better understanding of the dynamic range of the detector and offers a method to recover information lost to ADC saturation.

1 Introduction

The CHANDLER detector was designed to observe and measure the energies of electron antineutrinos produced by nuclear power plants. This detector consists of rows and columns of plastic scintillator cubes with wavelength shifting properties along with neutron detecting sheets between each row, essentially forming a box of these organic scintillators. This arrangement allows the detector to observe electron antineutrinos using its spatial segmentation through inverse beta decays (IBD), where a neutrino will interact with a hydrogen nucleus in the cubic scintillator, resulting in the production of a positron and a neutron. With these resultants, flashes of light are produced and transmitted in the detector using total internal reflection, which is then picked up by the PMTs at the sides of the detector.

The CHANDLER detector technology has shown promising results of making a suitable above ground detector that is small in size, highly efficient, and precise even in high background environments. Additionally, it uses minimal shielding, no overburden, and no liquid scintillators, allowing the detector to be easily implementable. Its applications are pertinent, from nuclear fuel monitoring to power monitoring as using this detector would eliminate the need to track a reactor's operational history in order to understand the composition of its fuel. This is due to the difference in neutrino signals and energy spectra that a core with an abundance of plutonium will emit versus a core rich in uranium [1].

That being said, there is a limitation to the data acquisition system used in the detector. The PMTs used have a dynamic range, particularly an upper threshold or a point of saturation. Energy depositions that exceed this value cause the data to flatline, which is transmitted as saturated data. This can occur when cosmic rays such as muons, a significant source of background, enter the detector and ionize, resulting in measurements of their energy that can exceed the upper threshold of the dynamic range. The data transmitted is hindered by saturation due to high signals, and pertinent information is lost as a result. Even so, applicable information such as waveform, length of saturation, and the RC nature of the electronics can aid in recovering missing ADC counts of these large signals.

This study aims to characterize saturation in the PMTs in order to understand higher energy depositions and signals in the detector by studying a system of two PMTs and comparing their data. By analyzing waveforms and applying curve fitting techniques based on the RC time constant, the original signal amplitudes that are beyond the dynamic range can be estimated, thereby improving data recovery as well as the detector's effective range.

2 Methods

2.1 Experimental Setup

The experiment set up consisted of 2 PMTs in a secured dark box, each with updated electronics including a high voltage board, high voltage disk, and logic board to power the PMTs and transmit the data. The saturated PMT, or PMT 1, was given the address 1111 while the unsaturated PMT, or PMT 2, was given 1122. The faces of the two PMTs sat across each other, separated by 3 cubic plastic scintillators. Lastly, an LED was held directly above the central scintillator using a plastic holder.

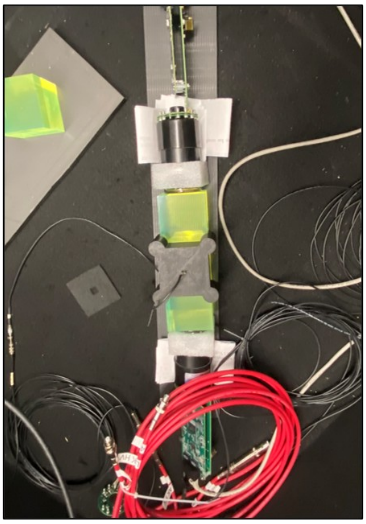

Figure 1: PMT 1 and PMT 2 were set up facing each other with an LED flasher and 3 scintillator cube in a dark box.

Before conducting the study, the gains of the two PMTs were matched using a constant controlled frequency of LED flashes at 1 kHz, powered by a DC voltage of 6.6 V. PMT 1 and PMT 2's gains were matched at 950 V and 1060 V respectively. Once the PMTs' gains were matched, a black square cloth matching the dimensions of the plastic scintillator was used to cover the face of PMT 2 with a 1 cm^2 cut out in the center. This was done so that the point of saturation of PMT 1 would be reached well before PMT 2.

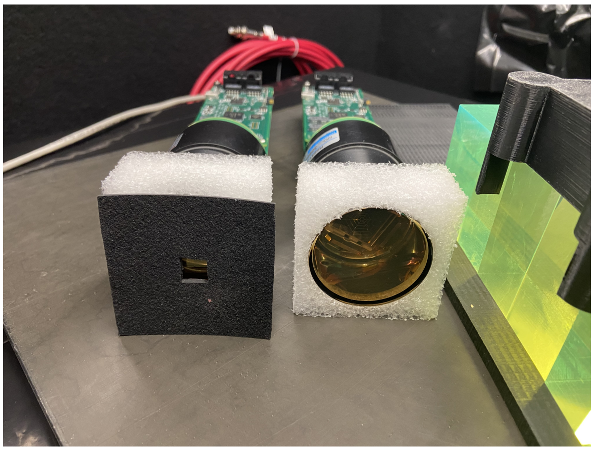

Figure 2: How the faces of the fully exposed PMT (PMT 1) and the partially exposed PMT (PMT 2) with a 1 cm^2 cut out were set up.

After the PMTs were set up in the dark box, additional coverings were added to the lid of the box in order to ensure no light leakages. Data was then collected, starting the voltage powering the LED at 6.6 V, and increased by increments of 0.05 V until it reached 7.6 V, with the same flash frequency used to match the gains.

2.2 Data Collection

Data was collected using 128 words per slice, with each slice containing 5 words of header. The flash rate of the data acquisition setup produced approximately 3 events per slice for each PMT, resulting in an average of over 12,000 events per PMT for each tested DC voltage. The raw data was stored as binary files and read out and checked in hexadecimal format for each LED voltage setting. A pre-coded binary data parser was used to extract and organize the information, including the ADC counts, timestamps, triggers, and PMT IDs. The processed data was then used to generate plots for further analysis.

3 Data Analysis

To characterize the response of each PMT, the maximum ADC values were extracted for each event in each PMT. For each voltage increment, a histogram of these values was constructed and each was fitted using norm.fit, a python function that estimates the mean (μ) and standard deviation (σ) to fit a normal curve over a masked range of data to minimize the influence of outliers and obtain a reasonable reduced χ^2 value. The gaussian model used was:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

After plotting the means of the maximum ADC values for each PMT on the same graph, dividing the maximum ADC values of PMT 1 by PMT 2 resulted in an average ratio of 31.19 within the unsaturated range (6.60 to 6.90 V). Using this ratio, the average maximum ADC values for PMT 2 were scaled and overlaid on the same plot alongside the unscaled values from both PMTs. The resulting scaled curve was used to represent the expected values in the saturated region of PMT 1, as it projects the values from PMT 2 that are within the dynamic range.

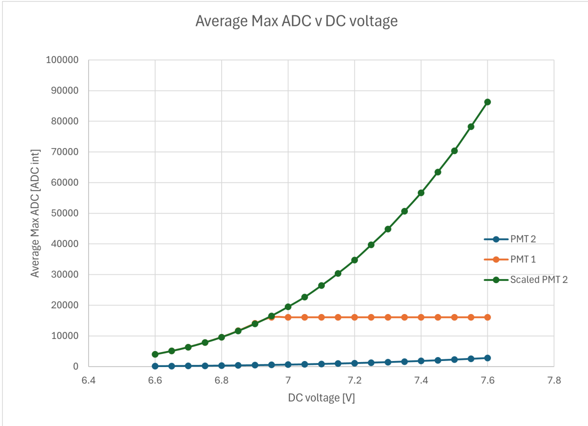

Figure 3: This plot is of the average max ADC count v DC voltage of PMT 1, PMT 2, and PMT 2 scaled. The plot shows the saturated region as well as the projected curve over this region forming the expected values.

Additionally, graphs of the waveforms were used to identify regions of saturation. In these plots, the waveform typically exhibits a gradual rise due to the integration time of the charge integrator, followed by a plateau of saturation at the ADC saturation limit of 16091. After this saturated region, the signal decays exponentially following that of an RC circuit. Utilizing the samples where it decays, the curve can be fitted and used to extrapolate backwards to where the waveform reaches its true signal peak: typically after the initial rising edge. This extrapolation method was performed with the exponential decay model using the following:

$$f(x) = Ae^{-\frac{t}{\tau}} + C$$

In this model, A represents the amplitude at the start of the decay, tau (τ) is the time constant, and C is the baseline offset. All three parameters were estimated using the first and last values of the tail region and a guess for τ. Events with only 3 samples to fit at the decay tail were excluded to ensure stability and accuracy. This predicted what the actual maximum ADC value would have been for events that are saturated. An average of these predicted peak values was computed and plotted with the scaled ADC counts from PMT 2 at the corresponding saturated DC voltages.

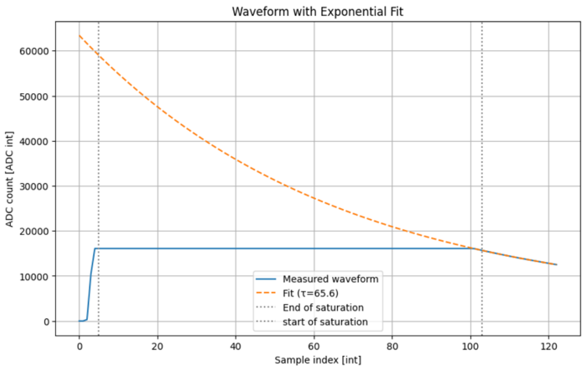

Figure 4: A visual example of using an exponential decay fit and the end of saturation to extrapolate backwards to predict the actual max ADC value.

4 Results

It was found that using a variable time constant (τ) resulted in poor fits for several waveforms, particularly at higher LED intensities. Each waveform contains just over 120 samples, but at high intensities, more than 100 of these can be saturated. This leaves only a few unsaturated samples available for curve fitting, potentially leading to unstable fits and large variation in the extrapolated ADC values. This is what resulted in such large variances in the extrapolated values and fits that failed to properly predict the ADC peak value.

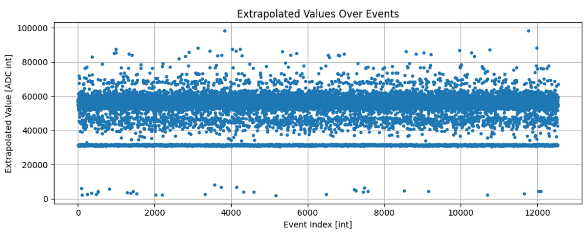

Figure 5: This plot is of the 7.6 DC voltage setting using a variable τ, highlighting the fits that failed (most notably the outliers deviating from the mean.)

To improve the fitting process, an average time constant was collected from the previous fits. Given the RC-circuit behavior of the electronics, τ is expected to be approximately constant. Fixing τ to a value of 68.58 produced clearer distributions of the extrapolated values and improved the stability of the fits.

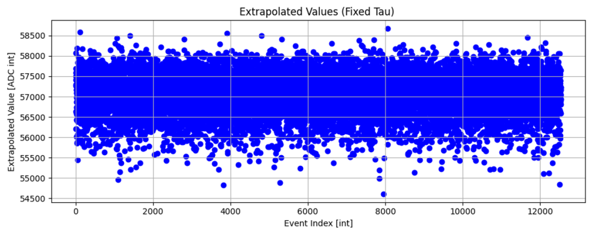

Figure 6: This plot is of the 7.6 DC voltage setting using a fixed τ with a cleaner distribution.

Finally, comparing the extrapolated values with the expected ADC values (derived from scaled PMT 2 measurements) shows good agreement at lower LED intensities. In the 6.95-7.2 V range, extrapolation closely follows the expected trend. However, at higher intensities, the predicted values begin to deviate, potentially due to the increasing saturation and reduced fitting accuracy.

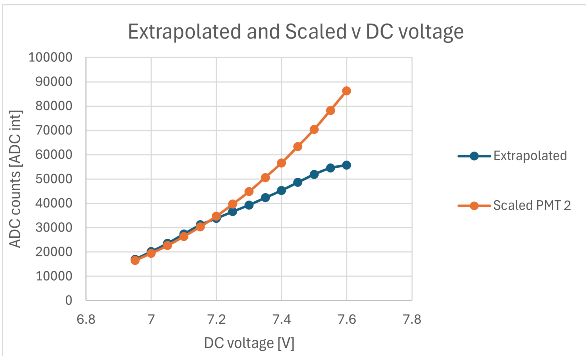

Figure 7: This plot shows the scaled ADC counts of PMT 2 (the expected values) and average extrapolated values for the saturated DC voltage range (6.95-7.6 V).

5 Discussion

The results show that extrapolation can be used to recover missing peak ADC values caused by saturation. However, the increasing deviation from the expected values at higher intensities warrants further investigation. A potential explanation is due to the lack of samples as saturation length increases, decreasing the number of samples used for curve fitting which would result in unstable fits and inaccurate extrapolated values. Another possible cause could be a result of nonlinearity due to the limitations of the electronics used.

In addition, resolution behavior was also examined. It was found that resolution of PMT 2 (the unsaturated PMT) closely follows a square root function, as expected for statistical photon processes.

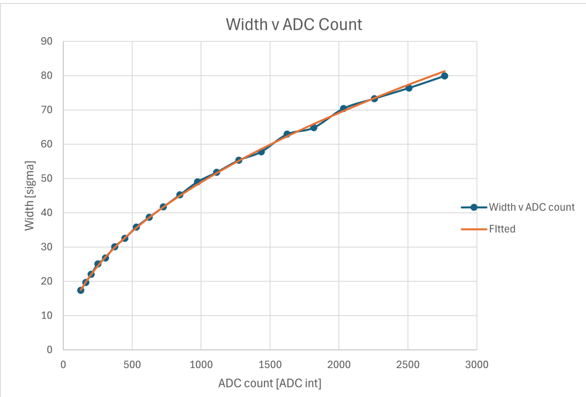

Figure 8: This plot shows the resolution of PMT 2 (the unsaturated PMT) following a square root function.

In contrast, the resolution of PMT 1, whose data required extrapolation, does not follow the same trend as predictably, suggesting further investigation is needed to understand the discrepancy.

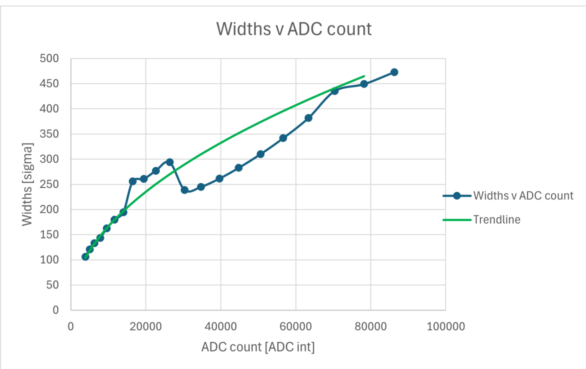

Figure 9: This plot shows the resolution of PMT 1 (the saturated PMT).

An additional observation involves estimating the ratio of average maximum ADC counts between the PMTs is by comparing the surface areas of their exposed faces. PMT 1, the fully exposed PMT, has a surface area of 20.27 cm^2 while PMT 2 has 1 cm^2, yielding a theoretical ratio of 20.27. However, this is different from the actual measured ratio which was notably higher. This discrepancy is likely due to the difference in gains of each PMT. Although they were roughly matched, each PMT's gain can vary due to factors such as manufacturing differences or environmental conditions such as temperature.

6 Conclusion

Extrapolation with a fixed time constant for a lower DC voltage range was shown to be an accurate way of recovering peak ADC values from saturated waveforms, particularly within the lower LED voltage range. In practice, waveforms rarely have up to 100 saturated samples which is where the extrapolated values deviate the most from the expected. Additionally, the plot of the scaled ADC values and extrapolated values (see Fig. 7) provides useful mapping for saturated signals, particularly in the nonlinear high intensity region. Overall, this method provides a practical approach for understanding the CHANDLER detector's dynamic range as well as extending it.

7 Acknowledgments

This work was supported by the National Science Foundation under grant no. PHY-2149165 and the Virginia Tech Center for Neutrino Physics under the Research Experience for Undergraduates (REU) program. I would like to thank my research mentor Dr. Jonathan Link, as well as Coco Ding for their guidance and support throughout this project. I am also grateful to Betty Wilkins and Dr. Thomas O'Donnell for coordinating the REU program and providing the resources necessary for a successful un-

dergraduate research experience.

References

[1] Alireza Haghighat, Patrick Huber, Shengchao Li, Jonathan M. Link, Camillo Mariani, Jaewon Park, and Tulasi Subedi. Observation of reactor antineutrinos with a rapidly deployable surface-level detector. *Phys. Rev. Appl.*, 13:034028, Mar 2020.