Development of Digital Pulse Processing algorithms for Muon detection and Pulse-height distribution estimation

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Abstract: We are in the process of upgrading laboratory equipment at Mexico city's Cosmic Ray Observatory developing our own instrumentation. Our approach to this task relies on Programmable Logic technology and Digital Pulse Processing techniques (DPP). An example of this is our new low-cost DAQ system (described in a separate paper [1]). The next step in the upgrading process is the design of nuclear spectroscopy systems for neutron and muon detectors at the Observatory. In the case of NM64 neutron monitor we can estimate pulse height distribution and evaluate the performance of a novel pulse pile up recovery algorithm (studying the possibility of using this system for other experiments). For the muon telescope we are designing a new method for separating the soft component from the muon component. In this paper we present the details of the algorithms and the first tests we made with signals from the detectors.

Keywords: Pulse pile-up recovery, Muon detection, Digital pulse processing

1 Introduction

1.1 Neutron Monitor

Neutron Monitors of the type NM64 are composed by an array of gas-filled Proportional Counters (PRCs) surrounded by a moderator, a producer and a reflector. The Monitor detect the thermal neutrons produced by nuclear reactions in the producer and the hard component of secondary cosmic ray. The total number of Neutrons is an estimate of the cosmic rays flux at the top of the atmosphere. The continuous operation of this instruments provide information about solar activity and the interplanetary medium.

A tool for studying the energy spectrum of Cosmic Rays and the response Function of the detector to primary Cosmic Rays is the pulse height distribution (PHD) of the detector[2]. Furthermore, in order to guarantee stable and reliable data from the monitor, it is important to perform maintenance tasks and analyze the response of the detector. With knowledge of the nuclear interactions in the tube, PHD may be used to detect degradation in the detector and/or associated electronics[3].

In cases where a detector is subjected to high counting rates, the time response of the detector and associated electronics (impulse response) could severely reduce the accuracy of the PHD due to pulse pile-up. In México City's Cosmic Ray Observatory we decided to implement a Spectroscopy system to estimate the PHD from the NM64. To correct the effects of pile-up from the detector we designed an algorithm based on Digital Pulse Processing techniques. This algorithm could be useful to estimate the PHD from other detectors subject to higher counting rates.

1.2 Muon telescope

Pulse shape discrimination (PSD) is a technique used to differentiate different kinds of particles analyzing the output waveform of the detection process. Usually this is accomplish digitizing the pulses from the detector and processing the waveform samples. However, this approach is challenging due to the need of high sampling rates (to preserve waveform information) and efficient algorithm for the analysis.

A muon telescope constructed in the top and bottom of a NM64 can separate the soft component of the secondary Cosmic Ray flux from the muon component. This method is based on the coincidence of signals from both ends of the telescope. The soft component is stopped by the lead around the NM64 while the muon component can penetrate. As a result, the top of the Telescope registers a combination of both components and the bottom only registers the muon component.

Using the muon telescope as particle identifier we develop a method to separate the soft component from the muon component usign PSD. To characterize the muon signal on the detector, we built a database of the waveforms from the bottom side of the telescope. With the muon signature on the PMT's we want to discriminate the soft component from the total flux registered by the top side of the telescope.

2 Method

2.1 Experimental set-up

The NM64 uses PRC's filled with BF_3. The output from one tube is integrated by a preamplifier stage and passes through a shaping-amplifier. The total combined gain of the circuits is about 200 with a fixed decay time-constant of $6.7\mu s$. The output pulse from the shaping amplifier is digitized using a Tektronix MSO2024 Mixed signal oscilloscope. The sampling rate used is $15MS/s$ with 8-bit resolution.

The Muon Telescope uses *NE102-A* Plastic scintillators of $50 \times 50 \times 5\ cm^3$. The decay time-constant of the scintillator is $3ns$. The detector uses PMT's of the type *Hamamatsu-R1512*. The output from one PMT is connected directly to the digitizer and no integration is performed on the signal. The sampling rate in this case is set to $125MS/s$ with 8-bit resolution.

A Personal Computer running linux and software written in Python (PyUSB) controls the capture of pulse waveforms and acquisition parameters. When a pulse with an amplitude greater than a threshold (fixed to eliminate electronic noise) occurs, the MSO2024 oscilloscope transfers the digitized waveform to the Personal Computer using a USB interface. The program is set to automatically capture waveforms for 5 to 10 minutes periods. Using this software we built a pulse waveform database from the NM64 and Muon telescope. The waveform data is analyzed with Python modules for numeric and scientific computation (*NumPy*, *SciPy* and *Matplotlib*). A schematic diagram of the electronics setup is shows in Figure 1.

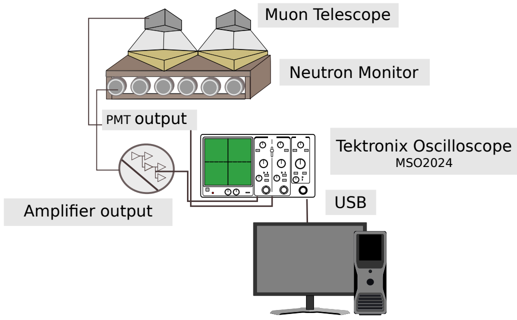

Figure 1: Schematic diagram of acquisition setup used. Waveform capture is one detector at a time

2.2 Pulse height distribution estimation

The process of detecting an incoming radiation signal may be modeled[4] as a signal $x(t)$ with an unknown number of radiation events of brief duration (delta-shape like), random amplitude and random time of arrival, interacting with the total impulse response $h(t)$ from the detector and electronic system.

$$y(t) = x(t) * h(t) + n(t) \qquad (1)$$

where $y(t)$ represents the detected radiation signal and $n(t)$ white Gaussian noise.

To estimate the PHD from $y(t)$ we must measure with precision the amplitude and time occurrence from each pulse. The impulse response $h(t)$ of the detection system sets the rise and fall time of the output signal $y(t)$, hence represents the main source of pulse pile-up. The signal $n(t)$ alters the pulse amplitude and generates small spurious pulses. Therefore, in order to accurately estimate the PHD, the effects of $h(t)$ and $n(t)$ must be minimized. Traditionally this is achieved applying a low-pass filter to the signal (to reduce high frequency noise), then shortening the length on the pulses (to minimize the effects of $h(t)$).

An alternative to this procedure (based on DPP) is to perform peak detection in $y(t)$. Figure 2 shows a schematic block diagram of a peak-detection unit.

Underneath we describe every block:

Smoothing Low pass filtering of the signal to minimize detection of false peaks generated from noise.

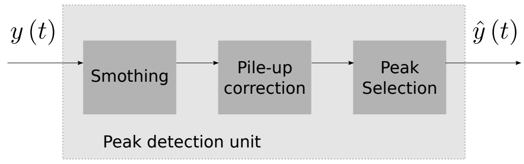

Figure 2: Peak detection technique

Pile-up correction Amplitude correction of every pulse to minimize the effects of pulse pile-up due to impulse response of the measure system.

Peak selection Selection criterion used to eliminate the remaining false detected peaks.

The continuous wavelet transform (CWT) can carry-out this operations on the signal with low false detection rate[5]. Mathematically the CWT is:

$$C(a,b) = \int_{\mathbb{R}} y(t)\, \psi_{a,b}(t)\, \mathrm{d}t \qquad (2)$$

where a is the scale, b position and $\psi_{a,b}$ is a scaled and translated wavelet. C is the $2D$ matrix of wavelet coefficients. The wavelet coefficients reflect the matching between $y(t)$ and $\psi_{a,b}$. Higher coefficients values indicate better matching. Using parameter a we can characterize peaks of different widths in the signal. Real peaks on the signal are detected with the CWT (large coefficient values) on a set of different scales, while false peaks are present only in a few scales. With this principle we can differentiate between real peaks (radiation events) and false peaks.

In the case of pulse pile-up, if we assume the baseline of a pulse slow changing and monotonic, CWT can automatically correct the amplitude of the pulse[5].

To estimate the PHD from the radiation signal using CWT we propose the next algorithm:

1. Carry-out a CWT on the radiation signal.
2. From the largest to the smallest scale (rows of the C matrix), identify the maximal coefficients on each scale.
3. Search for maximal coefficients in the same column on adjacent scales. Link them to form *ridge lines*.
4. The ridge lines must satisfy two conditions to be considered peaks:
   (a) Signal to noise ratio of the ridge line must be higher than a given threshold.
   (b) The length of the ridge line must be is larger than the threshold for the minimum length.

   The two parameters (SNR and minimum length) need to be adjusted to improve performance.
5. Calculate the histogram from the detected peaks of the signal.

2.3 Muon detection with pulse-shape analysis

The output signal $i(t)$ from a PMT coupled to some type of organic scintillator can be modeled as the superposition of two exponential decays[6]:

$$i(t) = A \cdot \exp\left(-t/\tau_f\right) + B \cdot \exp\left(-t/\tau_s\right) \quad (3)$$

τ_f represents the prompt decay constant of the scintillation and depends on the scintillator material. τ_s is the delayed decay constant it depends on the type of the exciting particle.

PSD is usually not carried-out with plastic scintillators[7] because the effect is smaller to that in liquid scintillators. However, it has been shown that the *NE102-A* plastic scintillator posses some PSD properties. Considering this, we proposed a method to detect muons and separate its signal from the soft component using a muon telescope.

1. Built a database of pulse waveforms from the telescope.
2. Extract the decay constants from the pulses.
3. Estimate the amplitude of the pulses.
4. With the amplitude and decay constant information run a clustering algorithm to separate the data on two groups: muon component and soft component.
5. Estimate the contribution of the muon component to the total flux.

To construct the pulse waveform database we capture signals from top and bottom layers (see Figure 3). The bottom signal will be used to characterize the muon signature because the soft component is stopped by the NM64 lead. The detection will be performed in the signal from the top layer

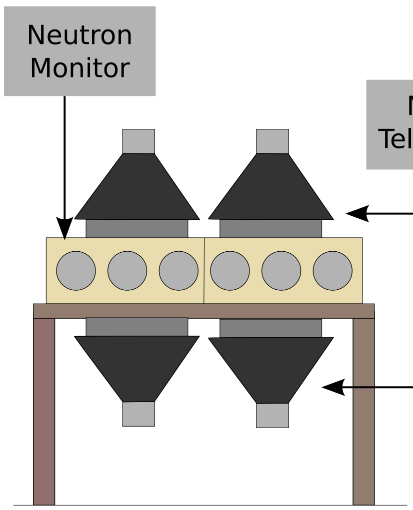

Figure 3: Schematic front view of the detector at Mexico City's Cosmic Ray Observatory

To extract the decay constants from the pulses we use a combination of the *Laplace transform* and *Padé approximants*[8]. The aim of this method is obtain the poles and resides from the Laplace Transform which correspond to the decay constants and amplitudes of the exponential components respectively.

The first step is to approximate the Laplace transform of a N-samples pulse $x(t)$ at point s_0:

$$\mathscr{L}\{x(t)\}(s_0) \approx \sum_{j=2}^{N-1} e^{-s_0 t_j} x_j \quad (4)$$

where x_j represent the samples from $x(t)$ and s_0 is the only input parameter to the algorithm. A good choice for s_0 is the inverse of the time it takes for the signal to decay $1/2$ its maximum value.

The next step is make a Taylor series expansion of $\mathscr{L}\{x(t)\}(s_0)$:

$$\mathscr{L}\{x(t)\}(s_0) = \sum_{j=0}^{k} c_j (s - s_0) \quad (5)$$

Finally we express the Taylor series as rational function. This function is known as the Padé-approximant:

$$\frac{a_0 + a_1(s - s_0) + \ldots + a_{n-1}(s - s_0)^{n-1}}{1 + b_1(s - s_0) + \ldots + b_n(s - s_0)^n} \quad (6)$$

Decomposition of the Pade approximant into its partial fractions gives the exponential decay constants as the poles and the amplitudes by the corresponding residues.

3 First results and further work

The software for waveform capture was written in Python with module *PyUSB*. This module allows simple USB communication using Linux library *libusb-1.0*. The software was tested with Fedora 16 and OpenSuse 12.3 and can perform up to 4 waveform captures per second. The waveform data is recorded in text files with information about trigger level, sampling rate and time capture of the waveform. Every waveform capture is composed of about 6000 samples.

The algorithms for PHD estimation and muon detection are still under development. This algorithms are all written in Python using NumPy and SciPy (specifically the module Signal from Scipy). We wrote a routine for CWT based on *FFT* algorithms for fast performance. We also wrote a routine to detect the peaks using ridge lines on the Wavelet spectrum. However this part of the software still needs to be tested in order to meet the optimum parameters. To do this, we made a program based on model 1 to simulate the signal from the detector and estimate its PHD with the CWT algorithm.

The first results of the algorithm are shown in Figure 4. The CWT is able to locate the approximate time occurrence of the pulses.

In the case of the muon detection algorithm, the model in 3 does not consider the effect from the impulse response of recording system. Our first goal is to obtain a more accurate model. We completed an electronic circuit simulation with SPICE to quantify the effect of the reading system in the pulse signal. With this information we can have a more realistic model.

We wrote a routine to extract the decay components from a multi-exponential pulse signal. However this routine has not been tested extensively.

Figure 5 shows the data acquired by the oscilloscope from the Muon detectors. To preserve the time profile of the pulses, we connect the reading system to the output of the PMT, before any amplification step. This reduces SNR of the signal and hence the need to restore the pulse.

To achieve this goal without affecting the waveform of the pulse we designed a finite impulse response filter (FIR). FIR filters have the property of linear phase.

4 Summary

Digital Pulse Processing algorithms allows the extraction of features from incoming radiation signals. In the case of signals from NM64 the process of detection may be modeled as the convolution of the impulse response of the detector with a pulse train of unknown amplitudes plus white Gaussian noise. Considering high counting rates, the response from the detector can degrade the accuracy of the PHD. An algorithm based on CWT minimize the effect of the impulse response and noise allows the reconstruction of the original radiation signal. We designed an algorithm based on this principles and tested it with the 6-NM64 at the Observatory. The evaluation of this algorithm in presence of high counting rates is still under development. Muon detection is accomplished using coincidence methods. However, PSD is an interesting alternative at lower cost. To perform this technique really Fast electronic circuits and Processing units are needed. Efficient algorithms need to be implement in order to carry-out this tasks in Real-time. We designed a method for particle discrimination using a Multi-exponential model for the output signal from a PMT. Decomposing this signal with the Padé-Laplace method yields the decay components of the pulse. Using this algorithm in conjunction with the properties of Muon telescope we expect to derive the Muon signature at the detector.

5 Acknowledgment

The author wants to thank the UNAM's Geophysics Institute and Faculty of Engineering for their support during this project. Also, i want to thank the Mexican Physics Society for the founds to attend ICRC. This work is supported by the National Council of Science and Technology (CONACYT) in México.

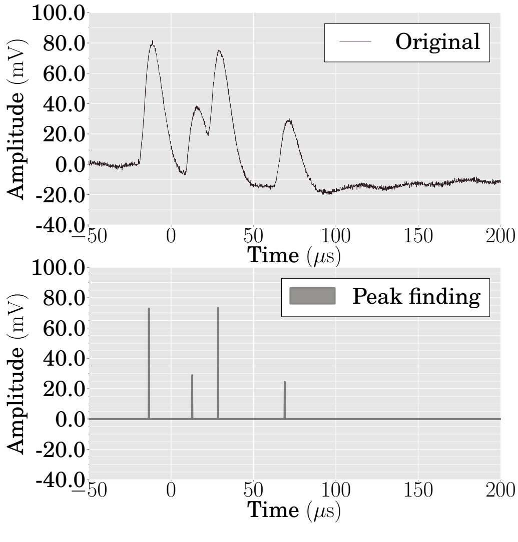

Figure 4: Pulse waveform data from the 6-NM64

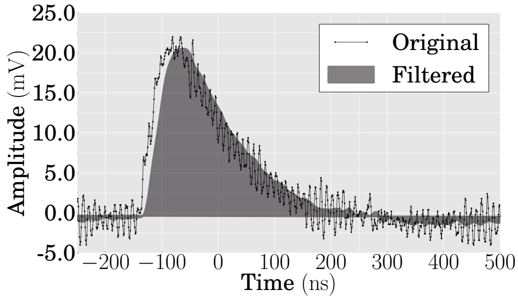

Figure 5: Pulse waveform data from the Muon telescope

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