

# Contents



# 1 Neural network training data

Over their relatively brief existence, neural networks have been shown to perform increasingly impressive tasks (e.g. [openai2019dota], [openai2023gpt4], and many more). However, they learn by example. The performance of a neural network is directly linked to the input data it receives during training. If the training data is not an accurate example of real world information a network later operates on, insight gained from it is at best an approximation, and at worst completely randomly generated data.

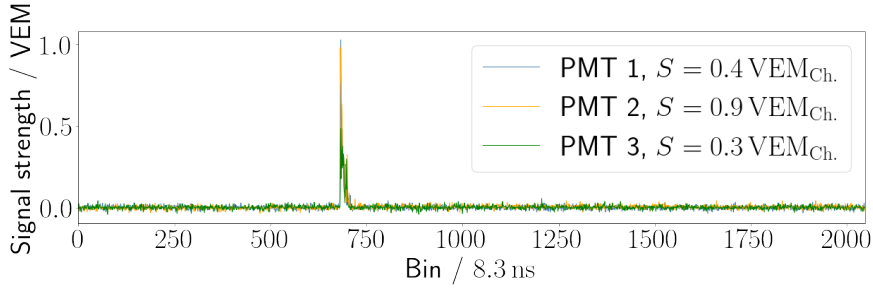
As such, it is not a question *if* some neural network architecture can learn to identify an extensive air shower from WCD data, but rather which implementation, fed with which information, does. For this purpose, this chapter explains the procedure with which training data is generated. As stated above, this must occur with a focus on being representative of data actually measured in the SD array. The elected approach to create time traces is modularized. The structure of this chapter reflects this. First, general comments about the characteristics of background data (i.e. the WCD detector response in the absence of an extensive air shower) are made in ???. Next, the process to extract signal originating from CRs is detailed in ???. Lastly, building the time trace from the aforementioned modules and drawing samples from it for a neural network to train on is done in ??.

## 1.1 Background dataset

While a flux of particles causes elevated ADC levels in both the HG and LG channels of a WCD PMT during a shower event, the lack of such a phenomenon does not imply the readout information is uniformly flat. Instead, it hovers around the channels' baseline (c.f. ??) with occasional spikes upwards due to low-energy particles impinging on the detector. Coupled with electronic noise from the many digital components in the UUB, this constitutes the data that is collected inbetween air shower events.

### 1.1.1 Accidental muons

Most low-energy background particles present in the detector are muons. These are produced in the upper atmosphere during cascading processes analog to ???. Due to the low primary energy the electromagnetic component of the shower is thermalized before it reaches surface level. The muonic component by itself does not contain enough information to enable an accurate reconstruction of primary energy and origin. This fact, coupled with the high flux of events at lower energies ( $\Phi|_{E=100\text{ GeV}} \approx 1\text{ m}^{-1}\text{ s}^{-1}$  [boezio2000measurement]) make these events unsuitable for analysis. Stray muons,



**Figure 1.1:** The simulated time trace from a single muon. The maximum peak of the time trace is equal  $1 \text{ VEM}_{\text{Peak}}$ . The integrated signal  $S$  is of comparable magnitude.

even though they originate from extensive air showers, must consequently be considered background events.

The rate at which such particles traverse a WCD tank is  $f_{\text{Acc.}} \approx 4.665 \text{ kHz}$  [**DavidInjectionFrequency**]. Their arrival time is Poisson-distributed. This implies that generally, one in 14 time traces contains signal from a low-energy background event. Coincidences of two accidental muons occur on a sub-percent level. Any higher order of coincidences is likely originating from a single air shower process. The typical signal recorded by the surface detector from a single muon is presented in ??

### 1.1.2 Electronic noise

Electronic noise is the umbrella term given to the distortions that some signal is subject to during digital readout. Such noise can have many different origins. An illustrative example is given by the **Laser Interferometer Gravitational wave Observatory**, which excludes the 60 Hz band and its' harmonics from analysis. This is owed to the fact that the DC frequency standard in the United States introduces systematic uncertainties in the detector [**martynov2016sensitivity**]. In the electronics of Pierre Augers' SD array, electronic noise is assumed to be Gaussian. That is to say that the ADC values of a time trace that was measured while no particle produced signal in the tank are normally distributed around the baseline. The standard deviation can be estimated from monitoring data, as is shown in ??.

### 1.1.3 Random traces

Both above mentioned phenomena can be simulated, and the simulation results used as background training data for the neural networks discussed in the next chapter. A more accurate method however, and the approach elected for this work is to utilize directly measured data from the field. Thanks to the work of David Nitz, there exist collections of so called random traces that were gathered by forcing DAQ readout via a manually set trigger.

In particular, two datasets of UUB random traces have been created until now. They were taken from 13th-18th March 2022, and 14th-18th November 2022 respectively. The first set contains data a total of sixteen million time traces distributed over four different SD stations. For reasons explained in ??, only data from the first set is used in the analysis presented in this work.

### Characteristics

Contrary to the naming of the random trigger, it occurs at a deterministic time. More accurately, the process of measuring random traces is as follows; A single time trace ( $2048 \cdot 8.333 \text{ ns} = 17.07 \mu\text{s}$ ) is written to the local station buffer every 10 ms. Once the buffer has accumulated enough data, it is written to a USB storage device. Because of a bottleneck in the last step, the process takes about 22 h per station [nitzCorrespondence].

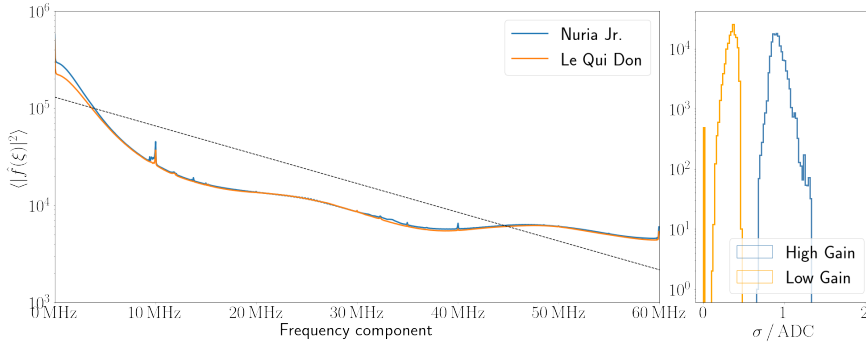
It is thus not the trigger that is unpredictable, but the data measured by each trigger. Due to the read/write process being independent of the measured data (as opposed to the algorithms in ??) the latter must be considered to be essentially random. For the most part, random traces are assumed to consist solely of electronic noise. However, signal of cosmic origin - be it accidental muons or extensive air showers - will appear in the data at a rate at least consistent with ??.

A crude analysis of the type of noise in the random traces can be made by examining the spectral density of the dataset, shown in ??. Harmonic modulations visible in both spectra might originate from an offset between last and first bin of the random traces. If this offset is nonzero, the periodic extension of  $f(x)$  exerts a step-function-like behaviour. The Fourier transform consequently reflects this [burrows1990fourier]. Still, several features of  $|\hat{f}(\xi)|^2$ , especially present at 10 MHz, imply the presence of systematic noise in the UUB. Nevertheless, the large scale form of the spectral density is compatible with at least two noise models, that cannot be distinguished based on the data at hand:

- $|\hat{f}(\xi)|^2 \propto \exp\left(-\frac{(\xi-\mu)^2}{2\sigma^2}\right)$ . The spectral density is Gaussian. This implies the noise is Gaussian distributed as well, confirming the assumption in ??.
- $|\hat{f}(\xi)|^2 \propto \exp(-m\xi + b)$ . The spectral density is proportional to  $\xi^{-n}$  for some power  $n$ . The case  $n = 2$  (-6 dB/Oct attenuation) seems to describe the observations well, hinting that the generating function could be Brownian.

### Calibration

The random trace files contain raw measurement data in units of ADC for the HG and LG channel of the three WCD PMTs. In a first step to standardize this information, the baseline is subtracted from each FADC bin. This is done via the baseline finding algorithm described in ?? and [tobiasBaseline, tobiasBaselineUUB]. Note that this approach differs from the baseline finding algorithm that runs on each station (c.f. ??).



**Figure 1.2:** (Left) The random trace spectral density for two stations. Plotted with a dashed black line is reference attenuation curve falling at  $-6$  dB/Oct. The spike at 10 MHz is of unknown origin and represents systematic noise in the UUB electronics. (Right) Example variance of all UUB stations in the surface detector array. The data shown in this plot was recorded on November 15th 2022 and is collected regularly via monitoring processes.

However, the difference is negligible ( $\ll 1$  ADC) for traces that do not contain any signal, which is the case for the vast majority of the dataset.

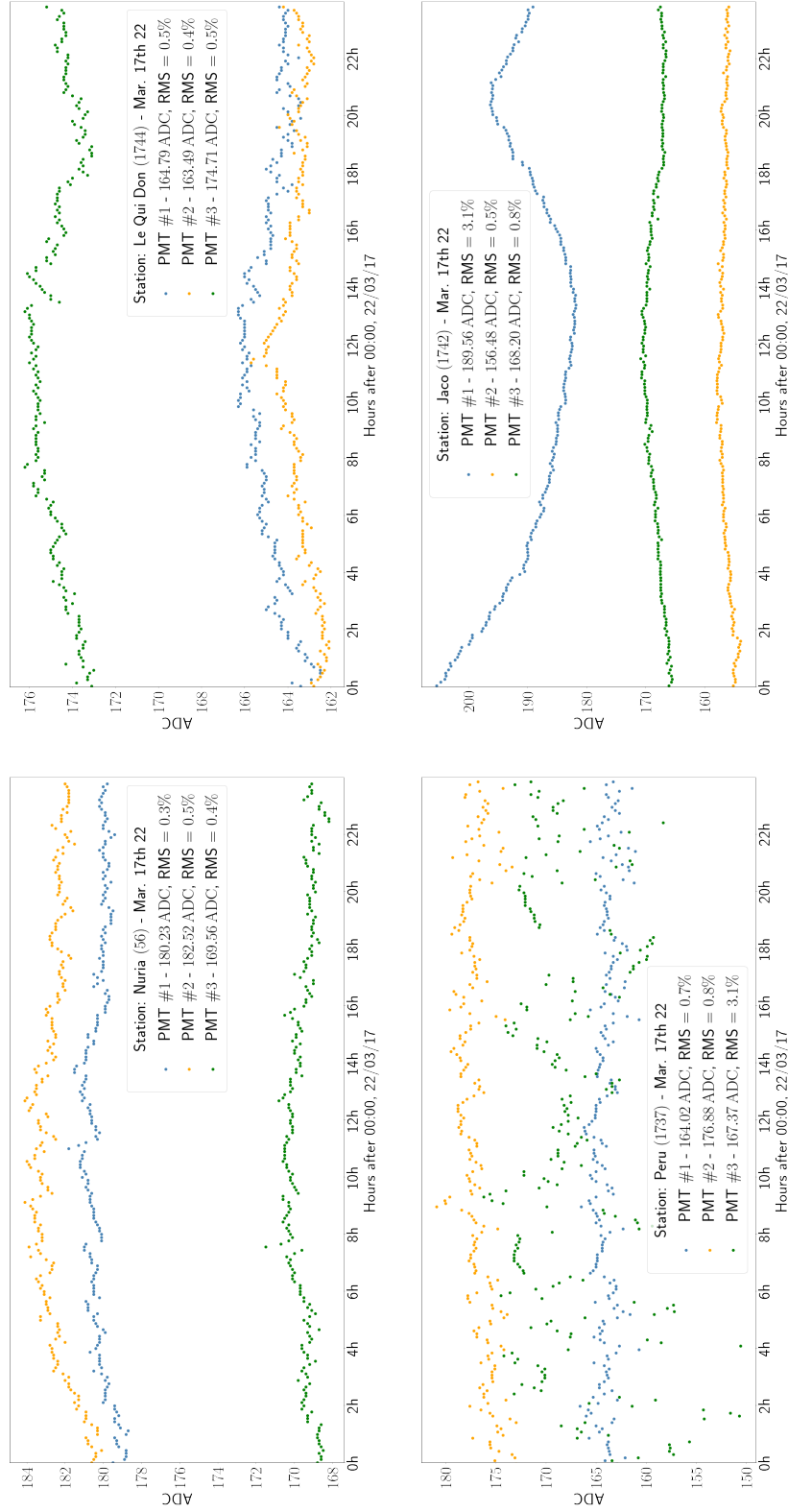
Next, the baseline-subtracted time traces are converted from units of ADC to  $\text{VEM}_{\text{Peak}}$ . This conversion is not straight forward, as it requires knowledge of  $I_{\text{VEM}}$  at the time of data taking. Each station estimates this value in periodic time intervals in the context of monitoring diagnostics.

For the second dataset of random traces (taken from 14th-18th November 2022) a UNIX timestamp packaged with each time trace may be related to monitoring data. This reveals that no information regarding  $I_{\text{VEM}}$  was forwarded to CDAS for any station while it recorded random traces. As a result, the entire dataset is unfortunately rendered useless for this work.

For the first collection of random traces, monitoring data is available, but there exists no timing information for the individual traces. Only the date of the measurement is known. The elected procedure to evaluate data as accurately as possible is thus to calculate the day average of  $I_{\text{VEM}}$  and  $Q_{\text{VEM}}$  and take this as the best (first) estimate for each trace. As can be seen in ??, this eliminates half of the remaining dataset, as two of the four stations show a large variance in  $I_{\text{VEM}}$ . The day average in these particular cases is not a good estimator for calibration purposes. For this reason, only random traces from the stations Nuria and Le Qui Don, measured in the March dataset, are used for analysis purposes.

As a crosscheck to verify the goodness of the approximation, the T2 trigger rate as reported by the calibration process is related to the trigger rate obtained by direct calculation over all (calibrated) random traces. By extension, this also serves as a unit test for the classical triggers as they are implemented in this work.

[to do: rate mismatch new plot]



**Figure 1.3:** Monitoring values for the four stations available in the random trace dataset measured in March '22. The bottom two stations show a large variance in  $I_{\text{VEM}}$  for at least one PMT. The two stations in the first row (Nuria, Le Qui Don) are more stable ( $\sigma / \mu < 1\%$ ).

## 1.2 Signal dataset

In the context of this work, a "signal" (as opposed to background) is any detector response caused by extensive air showers as simulated with CORSIKA [heck1998corsika]. Admittedly, this choice of classification is not ideal, as the particle density far from the shower core grows sparse. Time traces recorded at those locations look very similar to ones raised by accidental muons. In any case, ramifications and possible solutions are further discussed in the following chapters.

In order to isolate the detector response stemming from shower particles, a custom Offline simulation using Geant4

## 1.3 Trace building & Sliding window analysis