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CHARACTERIZATION OF LOW-DT NON-POISSON NOISE
IN THE ICECUBE NEUTRINO DETECTOR

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ABSTRACT

The IceCube Neutrino Observatory is a 1-cubic-kilometer neutrino detector constructed within the glacial ice at the South Pole. Two sub-detectors, DeepCore and the proposed Precision IceCube Next Generation Upgrade (PINGU), have been designed to probe low energy events in IceCube. However, these low-energy events are dim compared to higher energy events and require more advanced noise simulation and removal methods. This thesis details the methods by which distinctly non-Poissonian noise hits were extracted from 117.38 seconds of IceCube data. These noise hits, identifiable in the IceCube data stream by a sharp increase in hit rate over a short period of time, are referred to as “correlated noise.” By extracting a sizeable correlated noise sample, a full noise profile was created which shows the timing distribution of all observed noise in IceCube. The time separations of noise hits in this profile extend from $10^{-9}$ seconds to $10^{-1}$ seconds. There are four main components which contribute to the full IceCube noise signal—thermal noise, afterpulses, correlated noise, and long-timescale correlated noise. Thermal noise and afterpulses have been characterized in previous studies—it is confirmed in this thesis that thermal noise is accurately modeled by a Poisson process with a rate of 220 Hz, and afterpulses are accurately modeled by a Gaussian distribution with a mean time separation of 6 µs and a standard deviation of 2 µs. It is shown here that the correlated noise component is approximately modeled by a log-normal distribution with a mean of -6 and a standard deviation of 0.848, in units of $\log_{10}(\delta t/\text{sec})$. Currently, there are no physical hypotheses explaining long-timescale correlated noise timing distribution, but its smoothness suggests that it might be well-approximated by a closed-form expression. Further studies are needed to determine the origin of long-timescale correlated noise and quantify DOM-to-DOM variations in the low-$\delta t$ correlated noise region.
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Chapter 1

Introduction

The work within this thesis focuses on the extraction and parameterization of rapidly occurring noise hits in the IceCube Neutrino Observatory. Before a thorough explanation of the project can be given, some background information is necessary. This chapter presents an introduction to the IceCube Neutrino Observatory, the DeepCore extension, neutrino signals in IceCube, detector hardware, low-level IceCube data analysis, and an overview of the format of this thesis.

1.1 The IceCube Neutrino Observatory

IceCube is a neutrino telescope located within the glacial ice at the South Pole. Successor to the Antarctic Muon And Neutrino Detector Array (AMANDA), IceCube was built

Figure 1-1 The IceCube Neutrino Observatory, including the lab, IceTop, the main array, and the DeepCore extension (IceCube Gallery, 2011).
to detect neutrinos—small, electrically neutral leptons and potentially the most mysterious particles in the Standard Model of particle physics. IceCube consists of 5160 Digital Optical Modules (DOMs) suspended in the ice beneath Antarctica. The DOMs are organized in a lattice of 86 cables known as “strings.” Each string includes 60 DOMs spaced uniformly from a depth of 1450 m to 2450 m (Abbasi et al., 2009). A schematic of the IceCube detector can be seen in Figure 1-1. Figure 1-1 includes the deep “InIce” array, the surface “IceTop” array, and the DeepCore extension of IceCube. The InIce array, the principle subdivision of the IceCube detector, was designed to detect light produced during interactions that occur deep in the ice. The IceTop array was designed to detect high-energy cosmic rays in the atmosphere. It consists of two tanks placed above each of the IceCube strings—each filled with ice and containing two standard IceCube DOMs. DeepCore is an infill array near the bottom of IceCube which was designed to probe low-energy neutrino interactions.

IceCube was designed to act as a telescope and allow scientists to observe parts of the universe that have not yet been studied. Neutrinos, because they have small masses and no charge, are nearly immune to deflection by gravitational and magnetic fields, and they are rarely absorbed as they travel through the universe. This makes neutrinos ideal carriers of directional information. Direct neutrino detection is still a new enterprise—the construction of most large-volume water Cherenkov detectors like IceCube has occurred within the last 30 years.

There are several detectors that are similar to IceCube, including the Sudbury Neutrino Observatory in Ontario, Canada and the Super-Kamioka Neutrino Detection Experiment under Mount Kamioka in Japan; IceCube has the distinction of being the largest neutrino detector ever constructed. IceCube’s large volume allows for the study of very high energy neutrino events, including the PeV energy region. In addition to high energy neutrinos, IceCube is sensitive to massive dark matter particles, supernova explosions, and gamma ray bursts.
There are several reasons for constructing a detector within the glacial ice of the South Pole. The first is that the ice is very clear. Clear ice provides a clean sample for the IceCube detector and ultimately makes the detection of neutrino interactions easier. Second, it is very dark in the ice. IceCube DOMs are incredibly sensitive and must operate in the dark otherwise the signal will saturate and no neutrino events can be recorded. Finally, there is an incredible amount of ice available at the South Pole. Having such a large volume of ice allows for the production of more Cherenkov radiation which can be detected by the DOMs. The large volume also helps IceCube contain energetic events where particles are traveling near the speed of light.

1.2 DeepCore

A top-down view of the InIce, IceTop, and DeepCore infill arrays can be seen in Figure 1-2. Main IceCube strings are depicted as green, DeepCore strings are depicted as red, and the IceTop tanks are blue. Because of DeepCore’s increased DOM density, higher quantum efficiency photomultiplier tubes (PMTs), and deployment in the clearest ice in the detector, DeepCore is sensitive to neutrinos at energies over an order of magnitude lower than the original IceCube array (Abbasi et al., 2012). DeepCore’s low energy threshold allows the IceCube collaboration to explore atmospheric neutrino oscillations, and weakly interacting massive particles (WIMPs).
1.3 Neutrino Signals in IceCube

Most neutrinos travel through the Earth without interacting; however, there is a small probability that an interaction will occur via the weak force (Radel, 2012). Interactions which are observed in IceCube are classified as either “cascade-like” or “track-like.” The classification of neutrino interactions requires a basic understanding of weak interactions.

There are two mediators of the weak force: the electrically neutral Z-boson and the charged W-boson. Interactions in which a neutral Z-boson is exchanged are classified as neutral-current (NC) interactions. When a neutrino interacts with a target nucleus by exchanging a neutral Z-boson, the outcome is a neutrino and a resulting hadronic cascade (Beringer et al., 2012; Radel, 2012). The resulting neutrino leaves the detector and IceCube only observes the Cherenkov radiation resulting from the hadronic cascade. Events of this type are considered cascade-like events. Cascade-like events offer no information on the flavor of the incident
neutrino, because all of the observed Cherenkov light comes from interactions with the disrupted target nucleus (Beringer et al., 2012).

Interactions in which a charged W-boson is exchanged are classified as charged-current (CC) interactions. In a charged-current interaction, a neutrino interacts with a target particle to create a corresponding charged lepton (of the same flavor as the incident neutrino). To conserve charge, the target particle also experiences a change (e.g. neutron to proton). In a charged-current interaction, IceCube will detect Cherenkov light from the hadronic cascade triggered by the disturbed nucleus as well as the resulting charged lepton. This will create a distinctly track-like signature in the detector. Figure 1-3 shows a track-like and a cascade-like event.

![Figure 1-3 A track-like (a) and cascade-like (b) events in IceCube. Gray circles represent DOMs which did not observe any Cherenkov light. Those which were hit earlier are red, while those which were hit later are blue (Larson, 2013)](image)

Charged-current interactions convey information about the energy and flavor of the incident neutrino. To create a charged lepton, the incident neutrino must have energy greater than the rest energy of the charged lepton. Each charged lepton permeates the ice differently. Electrons and tauons have a short interaction length and are difficult to distinguish from the hadronic cascade, but muons tend to travel through the detector and leave a distinctly track-like impression (Larson, 2013).
1.4  Digital Optical Modules

Each DOM has a flasher board hosting 12 LEDs, a 13mm pressurized glass sphere, a 25 centimeter diameter photomultiplier tube, a 2 kV power supply for the PMT, and a main circuit board. A schematic illustration of a DOM can be seen in Figure 1-4. The LEDs can be used to calibrate other DOMs, simulate physical events, and examine the optical properties of ice. The glass spheres of the IceCube DOMs are pressurized using dry nitrogen. Pressurizing the glass spheres adds mechanical integrity to the DOM casing and allows it to be deployed into the ice (Abbasi et al., 2009).

![Figure 1-4 A schematic view of the IceCube DOM (IceCube Wiki, 2013)](image)

The PMT detects photons and outputs an electronic signal. Each DOM contains a mu-metal grid which shields the phototube from the Earth’s magnetic field, protecting the sensitive electronics. The DOM Mainboard is responsible for converting the PMT signal to a digital signal, which then gets sent to the IceCube lab via the path provided by the penetrator.

The DOM Mainboard is the central processor of the DOM. PMT signals are formatted by the DOM MB to create high-bandwidth waveforms that get captured by an application specific
integrated circuit, and then digitized. The data is temporarily stored in the DOMs physical memory until the Mainboard receives a request to transfer data to the main IceCube Laboratory (Abbasi & et al., 2009).

1.5 Digitizing the Signal

When a photon hits the photomultiplier tube in an IceCube DOM, electrons are produced via the photoelectric effect. Those electrons are directed toward a series of dynodes, where more electrons are produced. This creates a chain reaction where the signal from a single photon is amplified and converted to an electronic signal that can be digitized by the circuit board. When a DOM detects one or more photons, the digital output from the DOM is referred to as a “hit” (Abbasi et al., 2009). After a PMT signal activates a DOM, it is digitized by the Fast Analog to Digital Converter (FADC) or the Analog Transient Waveform Digitizer (ATWD) (Abbasi et al., 2009). Every hit is digitized by the FADC, but only some are digitized by the ATWD; this is because there is a long reset time each time the ATWD data is read. To minimize the effect of this deadtime, two ATWD chips are installed on each DOM mainboard.

Both the FADC and the ATWD are electronic elements of the DOM mainboard. ATWD readouts contain 128 samples with a bin size of 3.3 nanoseconds. Data readout from the ATWD can take up to 29 microseconds; this is the source of the aforementioned dead time. FADC readouts contain 256 samples with a bin size of 25 ns each, but there is no dead time associated with the FADC readout (Abbasi et al., 2009).

1.6 Local Coincidence

If a DOM observes a signal that is greater than or equal to 0.25 photoelectrons, the DOM produces a “launch.” Determining the local coincidence of DOM launches allows IceCube to handle the large amount of data that comes from each hit registered by a PMT. If a DOM launch is recorded, then nearby DOMs on the same string are checked for coincident launches. If
another launch is registered within two DOMs and within ±1 microsecond of the first launch, then
the launch is classified as a Hard Local Coincidence (HLC) hit (Larson, 2013). If those criteria
are not met, then the launch is a Soft Local Coincidence (SLC) hit. The waveforms of HLC hits
are digitized by both the ATWD and the FADC, providing a detailed readout of the DOM launch.
SLC readout only contains 3 of the first 25 samples of the SLC readout; those three samples are
the bin with the highest charge amplitude and the two neighboring bins. DOMs can operate in
several different local coincidence modes to reduce the amount of noise that gets sent to the
IceCube Lab; for instance, it is possible for the DOM to operate in nearest-neighbor local
coincidence mode in which the aforementioned logic is only applied to the DOMs two nearest
neighbors (Achterberg et al., 2006).

1.7 Triggers and Events

IceCube uses triggers to tell DOMs what to report and when. Several triggers are
processed with each DOM launch to build “events.” One of the simplest triggers is the Simple
Multiplicity Trigger (SMT) with a multiplicity of 8 (SMT8) (Larson, 2013). The SMT8 trigger is
applied when 8 HLC hits occur in the IceCube detector within 5 microseconds. A similar trigger
exists for the DeepCore detector called the SMT3 trigger. The SMT3 trigger is applied with 3
HLC hits occur in the DeepCore volume with 2.5 microseconds. Once the simple multiplicity
trigger condition is met, the detector readout is expanded to a ±10 microseconds window where
all HLC and SLC hits are recorded (Abbasi et al., 2012).

Fixed Rate Trigger (FRT) data is also useful for IceCube data analysis, particularly for
the study of noise in the detector. The Fixed Rate Trigger was implemented to create sets of data
that were minimally biased. When the Fixed Rate Trigger is activated, the IceCube detector
records data without interruption for 10 milliseconds. FRT data is recorded once every thirty
seconds and is not triggered by a physical event in the detector.
IceCube events are saved to files in frames which can store hit information in several different forms. It is standard for data acquisition (DAQ) frames to be preceded by frames containing information on the geometry, calibration, and detector status. Often, those frames are saved in their own files known as GCD files. For the sake of brevity, I will only explain two of the numerous object types that can be found in DAQ frames: I3DOMLaunches and I3RecoPulses. I3DOMLaunch objects store HLC and SLC information from events in the detector. I3RecoPulse objects store attempted reconstructions of the original photoelectrons detected by the PMT. The original photoelectrons are not stored directly in DAQ frames and therefore must be reconstructed from the digitized DOM readout.

1.8 Outlook

Chapter 2 of this thesis serves as an introduction to noise in IceCube—including both thermal (2.1) and correlated (2.2) noise as well as the new Vuvuzela noise module (2.4). Chapter 2 also includes an introduction to the HitSpool data format (2.3) which has been used in previous noise studies as well as this thesis.

Chapters 3, 4, and 5 contain discussions of original work completed for this thesis. Chapter 3 details the methods by which low-δt correlated noise events were extracted from Fixed Rate Trigger data from April 2013. This includes a more detailed description of the FRT data used for this study (3.1), the pulse selection criteria (3.2), local coincidence criteria (3.3), and pulse merging algorithm (3.5) developed to merge erroneously split pulses in this data set (3.4).

Chapter 4 presents the results of the methods described in Chapter 3. The first full IceCube noise profile is presented, combining the FRT study data and the HitSpool data used in previous noise studies (4.1). A possible parameterization of the full profile is also presented (4.2).

Chapter 5 includes a short summary of the work done in this thesis, as well as brief descriptions of possible future studies related to low-δt correlated noise.
Chapter 2

Noise in the IceCube Detector

Due to the rarity of neutrino interactions, it is necessary for experiments like IceCube to have a thorough understanding of noise in the detector, and a comprehensive method of negating the effects of that noise. This chapter will include discussions of thermal and correlated noise, data used for low-level noise studies, Monte Carlo simulation of observed noise, limitations of IceCube’s existing noise simulations, and noise removal methods.

2.1 Thermal Noise

Thermal noise is present in every photomultiplier tube. It is caused by the thermionic emission of electrons from the surface of the detector hardware. When the free electrons in a metal surface gain enough kinetic energy to overcome the metal’s work function, a thermionic current can be created. The emission of electrons from a metal surface is a Poisson process that strongly depends on the temperature of the metal. First described by physicist Owen Richardson, the thermionic current caused by the spontaneous emission of electrons follows Richardson’s Law: equation 2.1 (Richardson, 1901).

\[ J(T) \propto T^2 e^{-\frac{W}{k_B T}} \]  

(2.1)

In equation 2.1, \( J(T) \) is the thermionic current rate, \( T \) is the temperature of the metal, \( W \) is the metal’s work function, and \( k_B \) is Boltzmann’s constant.

Spontaneous emission of electrons from IceCube PMTs creates a measurable current in the absence of light called the “dark current.” The effect is somewhat suppressed because of the operating temperature of IceCube DOMs, which is between -40º C and -20º C (Abbasi et al., 2009). This process is well understood and simulated in the IceCube detector. However, there is
a non-Poissonian component of noise from a photomultiplier tube which dominates at lower temperatures.

### 2.2 Correlated Noise

It has been known since the deployment of AMANDA DOMs that, at low temperatures, there is a distinctly non-Poissonian component to the PMT dark current (Helbing et al., 2003). Recently, with the deployment of DeepCore (and the proposed PINGU extension), low energy detector simulations have become necessary. Because low energy events are dimmer in the detector, the effect of non-Poissonian noise becomes more apparent as we push to lower energies.

Professor David Seckel of the University of Delaware determined that there is a significant amount of correlated noise measured by IceCube DOMs. Results of Seckel’s work can be found in Figures 2-1, and 2-2.

![Figure 2-1 Hit Index (equals 1 for the first hit, 2 for the second hit, etc.) modulo 50 versus Hit Time. Non-Poissonian hits are noticeable as clusters of closely spaced hits. The diagonal lines represent a pure Poisson process with a rate equal to 220 Hz (Larson, 2012).](image)
Figure 2-1 shows the hit index (modulo 50) versus the hit time for a single IceCube DOM. The first hit registered by the DOM is given a hit index of 1; the second is given a hit index of 2, etc. The correlated noise hits are recognizable as clusters where the hit rate increases dramatically over a short period of time. The blue lines represent the expected pure Poisson rate of 220 Hz. It is clear from this figure that these noise hits do not follow a Poisson process and are not the result of thermal noise.

Figure 2-2, also the result of Seckel’s work, shows the extent to which these correlated noise hits affect IceCube’s data readout.

It is clear from Figure 2-2 that largest contribution from correlated noise hits comes from hits that are very closely spaced in time; this is consistent with the clustering mechanism shown in Figure 2-1. In the region $\Delta t < 1.5$ milliseconds, the thermal noise model drastically underestimates the amount of noise hits that are actually observed. The discrepancy is almost 2 orders of magnitude.
in the lowest $\Delta t$ region. This non-thermal dark current has been reported in other photomultiplier tube studies; however there is currently no consensus on its source (Meyer, 2010).

A detailed study of spontaneous electron emission from the surface of a PMT is described in Meyer (2010). The results of this study can be found in Figure 2-3.

![Figure 2-3](image_url)

Figure 2-3 Dark rate per cathode area observed with two Hamamatsu R7725 tubes. Tube 1 was cooled to 4K—the results of this experiment are shown as triangles. Tube 2 was cooled to 81K and then warmed up again—cooling data is represented by squares and warming data is represented by diamonds. Dashed lines represent expectations for thermionic emission. Circles and crosses represent similar measurements made with different PMTs (Meyer, 2010).

Figure 2-3 shows that although different PMTs may have different dark rates, the dark rate divided by the cathode area is the same for all tested PMTs. Through this study, Meyer was able to further distinguish correlated noise hits from thermal noise by showing a negative correlation between temperature and noise rate. Additionally, Meyer’s study concluded that the emission rate increases, independently of the electric field at the cathode surface, as the area of the emitting surface increases. This is also distinct from the behavior of thermionic emission, which increases
by an order of magnitude as the voltage is raised by 25% (Meyer, 2010). This phenomenon is caused by the electric field associated with a positive voltage pulling electrons free of the metal.

This effect was observed in IceCube DOMs in a study conducted at the University of Wisconsin – Madison. The results of that study can be found in Figure 2-4.

The data in Figure 2-4 confirms that IceCube DOMs do, in fact, increase in noise rate as the temperature falls. The data also shows that increasing the dead time (an artificial time interval after each recorded hit during which no other hits are recorded) of the DOM reduces the noise rate. This further reinforces the assumption that correlated noise occurs with very small δt intervals. Furthermore, removing the pressurized glass sphere from the DOM decreases the correlated noise rate. It was also found that irradiating the glass of the DOM increased the noise rate, whereas the inclusion of light-tight foil between the irradiated glass and PMT completely eliminated the clustering noise hits (Helbing et al., 2003). For this reason, it is hypothesized that the increased hit rate at low temperatures is due to a radioactive process triggering scintillation within the glass sphere of the DOM. This hypothesis seems probable because the glass is likely
to contain $^{40}$K, $^{238}$U, $^{232}$Th and several other radioactive isotopes (Helbing et al., 2003). However, because the noise was eliminated by the inclusion of light-tight foil, it is unlikely that the products of a radioactive decay are causing noise hits directly.

Further studies of the radioactive decay process were conducted by Helbing et al., 2003. The time structure of the luminescence by $^{40}$K decays in the ice at the South Pole is shown in Figure 2-5. The plot in Figure 2-5 shows signals digitized by both ATWD and FADC in AMANDA’s string 18. This study determined that the rate of scintillation light is parameterized well by a power law, where the initial hit is the result of the radioactive decay, and the following correlated hits are due to scintillation in the glass. The time interval over which scintillation light is observed spans almost two orders of magnitude, implying that there can be long times between

![Graph showing time distribution of pulses following the initial decay in AMANDA's string 18 (Helbing et al., 2003).](image)
hits in clusters. The lack of a physical explanation for correlated noise makes simulation a challenging task.

2.3 HitSpool Data

Noise studies are difficult to conduct because much of IceCube’s triggering mechanisms are designed to reject low-level noise. For this reason, it is necessary to use a different, untriggered data set to accurately assess the influence of noise in the IceCube detector.

HitSpool data was specifically designed with detector noise studies in mind (Heereman, 2013). During Hit-Spooling, all DOM output gets recorded and sent to the IceCube laboratory. To accommodate the large amount of data, none of the recorded hits are digitized by the ATWD. This effectively records every hit at an SLC hit regardless of local coincidence. Example HitSpool readout can be found in Figure 2-6.

Using HitSpool data, it was possible to see the full extent to which correlated noise affects IceCube data. Figure 2-6 shows two very clear peaks in the time between hits distribution. The peak centered about -2 shows the contribution from thermal noise, while the truncated peak...
centered about -5 shows the contribution from correlated noise. The fundamental limitation of this form of data is the time-spacing resolution. The distribution drops abruptly to zero as the hit spacing gets too small to be read by SLC readout (Δt < 2 microseconds). It is known that correlated noise extends far below this limit; some correlated noise hits occur within nanoseconds of each other. Because of this limitation, the histogram shown in Figure 2-6 does not represent a full profile of noise in the IceCube detector.

Noise studies done with HitSpool data have conclusively shown that IceCube’s original simulation method, which only included contribution from thermal noise and PMT after-pulsing, was insufficient. Some results from such a study can be seen in Figure 2-7.

![Figure 2-7 Time between hits for DOM 34-19. The black line shows HitSpool data while the red line shows IceCube’s older noise simulation (Noise-Generator) (Larson, 2013).](image)

Clearly, the thermal noise plus after-pulsing model does not accurately simulate all of the noise in the IceCube detector. For this reason, a new noise simulation method has been developed that more accurately depicts the distribution of noise hits in IceCube.


2.4 Noise Simulation with Vuvuzela

The Vuvuzela module is the current version of IceCube noise generation, developed and maintained by Michael Larson. The Vuvuzela noise model uses three separate components to create a full noise profile: thermal noise, radioactive noise, and correlated scintillation noise.

Thermal noise is generated according to a Poisson process. The number of hits in the simulation window is drawn from a Poisson distribution with a rate that depends on the temperature of the DOM, and those hits are uniformly distributed throughout the simulation window. The thermal noise rate is typically on the order of 20 Hz (Larson, 2013).

A second Poisson process is used to describe the radioactive noise. The number of hits due directly to the radioactive decay is drawn from a Poisson distribution with a rate that does not depend on the temperature. Those hits are once again uniformly distributed throughout the simulation window. The rate of radioactive decay is significantly higher than the thermal noise rate; radioactivity typically occurs with a constant rate of approximately 250 Hz.

A third Poisson distribution is used to determine the number of correlated hits that will occur following an initial radioactive decay. The mean of this distribution is a constant, reflecting the number of photons that reach the PMT from the scintillation process in the DOM glass. The mean is determined from an empirical fit for each DOM and has a typical value of approximately 8 (Larson, 2013). Because the more closely spaced correlated noise hits reach the PMT first (see Figure 2-5) these hits are not uniformly distributed throughout the simulation window. Rather, the time separations between hits are generated using a truncated log-normal distribution. Those hit separations are then sorted before actual hit times are calculated. The log-normal distribution used to characterize the hit separations has no physical significance and was simply extracted by fitting data.

The Vuvuzela module requires five parameters for simulation: the average rates for thermal and radioactive decay processes, the mean number of correlated hits due to scintillation,
and the mean and variance for the log-normal distribution. Other detector effects, including the effects of DOM electronics and the PMT response, are simulated in separate modules. Using HitSpool data, the correlated noise model parameters for each DOM were fitted individually.

The Vuvuzela modules begins by first simulation 100 ms of correlated noise hits, which are then stored and used in subsequent frames. Vuvuzela noise is then processed through the DOMLauncher module to simulate detector effects. Because of the limitations in the DOMLauncher module, each frame simulated by Vuvuzela can only have a maximum length of approximately 100 ms. Therefore, many frames must be simulated and merged to produce enough hits for the results of the simulation to be valid. If Vuvuzela simulates hits that occur outside of the simulation window, then those hits are kept and used in subsequent frames. This ensures continuity between frames. The results of Vuvuzela simulation for DOM 34-19 are shown in Figure 2-8.

![Figure 2-8 log10(Δt/sec) distribution including HitSpool data (black), Noise-Generator simulation (red), and Vuvuzela simulation (blue) for DOM 34-19 (Larson, 2013).](image-url)
Clearly, the Vuvuzela model provides much more accurate simulation than the Noise-Generator model. By overcoming the low Δt limit imposed by the HitSpool data format, new fit parameters can be added to the Vuvuzela model, determined for each DOM, and added to GCD files used by the collaboration for simulation.
Chapter 3

Measurement of Low $\delta t$ Correlated Noise

The study of low $\delta t$ non-Poisson noise in the IceCube detector was motivated by the artificial cut-off imposed by the HitSpool data format ($\delta t$ above $\sim 10^{-5.6}$ seconds). Characterizing the noise that occurs below this cutoff is essential for creating a full description of noise in the IceCube data readout.

It was necessary to create a novel data set for this study because much of the IceCube software and hardware framework is specifically designed to remove low-level noise. This data set had to meet 2 main criteria:

1) The data set had to be minimally biased. Many of IceCube’s triggering and processing algorithms are designed to create data sets useful for specific purposes. For instance, to conduct a study on $\nu_\mu$ events in the detector, certain triggers and cuts might be applied to the raw data to create a data set that contained many $\nu_\mu$ events and very little noise. In order to study the basic operation of IceCube DOMs, it was necessary to create a data set that was essentially an unbiased “snap shot” of the detector.

2) The data set had to include noise hits which were recorded with precision greater than 2 $\mu$s. This precluded the use of HitSpool data which had been used in earlier correlated noise studies.

The following sections discuss details of the data set used for this analysis, the methods by which pulses were selected from that data set, the local coincidence and isolation cuts used, the occurrence of pulse splitting, and the pulse merging algorithm developed to recombine
erroneously split pulses. At the moment, no attempt has been made to explain the obtained results from an underlying physical process.

3.1 FRT Data

In order to conduct this study, a large amount of unbiased data was needed. For this reason, Fixed Rate Trigger (FRT) data was used because it is not triggered by a physical event in the detector. Fixed Rate Trigger events are recorded for 10 ms every 30 seconds for every DOM in IceCube. Files containing only this unbiased data were created by extracting all events which passed the Fixed Rate Filter in data runs 122127 through 122165 which were recorded between April 1st and 10th, 2013. Because the IceCube data stream does not include the original photoelectron waveforms, but rather the digitized waveforms from the ATWD and FADC, I3RecoPulses were used in this study. The I3RecoPulse object is a reconstruction of the original photoelectron distribution observed by the PMTs, created after detector effects are applied by the waveform digitizers.

At the time that these data runs were recorded, I3RecoPulse timing information was stored in a float object. This presented a problem for accurately creating time distributions where hits were separated by nanoseconds because float objects only have 7 decimal digits of precision. It was determined that the rounding errors resulting from the limitations of the float data type became noticeable at later points in the FRT readout, so only the first 5 ms of each FRT frame were used. Since April 2013, the IceCube collaboration has changed to storing the timing information in a double object, which offers about twice the precision of a float object.

3.2 Pulse Selection

The pulse selection methods for this study were inspired by one of IceCube’s noise removal methods known as the Classic RT-cut (radius-time) module. This module removes noise from IceCube data by discarding pulses which do not have another pulse 1) within a designated
radius and 2) within a designated time “distance.” By creating a version of this module which
keeps spatially and temporally isolated pulses and discards coincident pulses, it was possible to
reject most of the physics-related events from the FRT data. For this study, pulses were kept
from the FRT frames only if they had exactly one neighboring pulse on a different DOM within
300 meters and 5 µs of the original pulse. Requiring that each pulse have precisely one
neighboring pulse on a different DOM increased the probability that the kept pulses would be
digitized by the ATWD and have suitable timing precision. In order to reject more physics hits,
the R and T parameters should ideally be increased such that only the most isolated pulses are
kept. However, isolation criteria which are too harsh reject too many hits, decreasing the
probability of ATWD channel readout and leaving too few statistics. Using a radius of 300
meters and a time window of 5 µs rejected nearly 100% of the physics signal while still accepting
enough hits to produce reliable statistics.

It has been shown in previous studies that the PMT dark rate for every IceCube DOM is
approximately constant (Helbing et al., 2003; Larson, 2013). Using the assumption that all
DOMs behave similarly, a detector-wide δt distribution was made by summing over the δt
distributions of each individual DOM. The δt distribution was computed as shown in Figure 3-1.

Timing information was extracted from the I3RecoPulse frame object. The δt distribution was
then calculated from the ordered pulses by measuring the time interval between consecutive
pulses.
3.3 Local Coincidence Criteria

Several different $\delta t$ distributions were computed from the FRT data set according to Local Coincidence criteria. Time intervals between consecutive pulses were calculated for all pulses, pulses digitized by ATWD, and pulses digitized using FADC separately, as seen in Figure 3-2.

It is important to note that the $\delta t$ distributions calculated using only pulses which were digitized by the ATWD or the FADC channels do not capture all of the features of the full $\delta t$ distribution using all of the pulses. For this reason, another $\delta t$ distribution was calculated using all pulses which were flagged as HLC pulses by the detector (meaning that they passed the HLC criteria as described in section 1.6).

The $\delta t$ distribution calculated using all HLC pulses is shown in Figure 3-3.
The distribution shown in Figure 3-3 is the $\log_{10}(\delta t/\text{sec})$ distribution for all HLC pulses which have passed the isolation criteria placed on the FRT data. In Figure 3-3, $\log_{10}(\delta t/\text{sec}) = -6$ corresponds to a $\delta t$ of 1 µs.

An HLC hit leads to a full readout of the ATWD and FADC channels. The longest combined readout time for an HLC event would require both ATWD chips and FADC chip to fully sample the event. This implies that the longest readout window for an HLC event is approximately 6.4 µs. This feature is present in Figure 3-3 as a sudden drop around $\log_{10}(\delta t/\text{sec}) \approx -5.19$.

Other prominent features of this plot include the sharp peak around $\delta t = 10$ ns and the broad peak around $\delta t = 1$ µs. Presently, it is thought that the broad peak around 1 µs is an actual feature of the noise and that the sharp peak around 10 ns is due to erroneous pulse splitting occurring in the data.
3.4 Split Pulses

Often when I3RecoPulses are reconstructed from the waveforms recorded by a DOM’s FADC and ATWD digitizers, the waveforms are erroneously split into two or more separate pulses. To understand why, it is necessary to understand the module which reconstructs the pulses: WaveDeform.

WaveDeform is a linear algebra-based algorithm designed for the deconvolution of a DOM’s response to individual photons. Signal from individual photons hitting the photocathode of IceCube’s PMTs gets obscured by the effects of the digitizers; WaveDeform attempts to recover this signal using the least squares fitting algorithm (Larson and Hanson, 1974). The digitized waveform from the DOM readout is fitted with the expected waveform for a single photoelectron (SPE) pulse by minimizing the sum of the squares of the offsets between the observed and expected waveforms. When the observed waveform does not match the expected SPE waveform precisely enough, the fitting algorithm can and will incorrectly split pulses. Despite this flaw, WaveDeform was used in this data analysis because it allowed the recovery of the original $\delta t$ distributions for single photoelectron pulses.

Split pulses are generally characterized by low $\delta t$ values and low pulse charge. Figure 3-4 shows that most of the pulses in the sharp peak around $\delta t = 10$ ns have an unusually small charge.
The low pulse charge indicates that the pulses were most likely not properly reconstructed by WaveDeform. Additionally, the PE $< 0.3$ peak occurs in a $\delta t$ region far lower than any known PMT effects.
By examining pulse waveforms from the ATWD and the FADC channels separately, it was shown that pulse splitting occurred mostly in pulses digitized by the ATWD. The results of this study are shown in Figure 3-5.

![Graph showing log10(δt/sec) distributions](image)

Figure 3-5 Separate log10(δt/sec) distributions for all HLC pulses, ATWD pulses, and FADC pulses. Note that the ATWD pulse and FADC pulse distributions do not add to the HLC pulse distribution because there are several δt intervals which contain one ATWD pulse and one FADC pulse.

The δt distributions shown in Figure 3-5 were calculated by computing the time interval between consecutive hits as shown in Figure 3-2. According to these results, pulses are being split from the ATWD readout but not from the FADC readout.

In order to create an accurate log10(δt/sec) distribution for single photoelectron noise hits, these split pulses had to be merged. The following section describes the algorithm used to merge split pulses.
3.5 Pulse Merging

A pulse merging module exists as part of the PINGU processing tools, designed for the study of low energy events in the proposed IceCube extension. This algorithm is designed to merge split SLC pulses. It is a simple algorithm which combines pulses based on the time difference between adjacent pairs of SLC waveforms. If the time difference between a pair of SLC pulses is smaller than one microsecond, then those pulses are combined into a single pulse. If consecutive pairs of pulses all meet the one microsecond criteria, then they are all combined into a single pulse. The new combined pulse has the following characteristics:

\[ Q = \sum_i q_i \]
\[ T = \frac{\sum_i q_i t_i}{\sum_i q_i} \]
\[ W = \sum_i w_i \]

where \( Q \) is the pulse charge, \( T \) is the pulse time, and \( W \) is the pulse width. The combined pulse charge is the sum of the individual charges, the combined width is the sum of the widths, and the combined time is the average time weighted by the pulse charge. Similar logic was used to create a pulse merging algorithm for merging accidentally split ATWD SPE pulses. However, this required a more detailed study of the pulse charge distribution.

Because the \( \delta t \) distributions are calculated for pairs of pulses, there are two pulse charges that are of interest to the pulse merging algorithm. Those pulse charges, referred to in this thesis as \( Q_1 \) and \( Q_2 \), correspond to the earlier and later pulse in the \( \delta t \) interval, respectively. Figure 3-6 shows the \( Q \) vs. \( \log_{10}(\delta t/\text{sec}) \) distributions for both \( Q_1 \) and \( Q_2 \). In Figure 3-6, the z-axis is represented by the colors displayed to the right of the main plot – darker blue corresponds to more entries. It is clear that there are some mistakenly split pulses because for an SPE distribution, one would expect the charge distribution to be normally distributed about \( \sim 1 \) photoelectron (PE).

Regions of this plot selected for pulse merging are enclosed by red rectangles in Figure 3-6. The aforementioned pulse merging algorithm had to be changed to account for charge...
distributions which were not the same for $Q_1$ and $Q_2$. The pulse merging criteria shown in Figure 3-6 select pulses which occur with $\delta t < 71$ ns (corresponding to $\log_{10}(\delta t/\text{sec}) \approx -7.15$) and $Q_1 < 0.5$ PE or $Q_2 < 0.25$ PE. These values were empirically determined from the charge distributions of the pulses.

Pulses which lie in either of the split pulse regions were selected for merging. The results of the pulse merging algorithm using these criteria are shown in Figure 3-7 and Figure 3-8.
It is clear from the distributions shown in Figures 3-7 and 3-8 that the initial pulse merging criteria shown in Figure 3-6 identified most, but not all, of the split pulses. Figure 3-7 still shows an excess of pulses near $\log_{10}(\delta t/\text{sec}) = -8$ which corresponds to the split pulses peak identified previously. However, the magnitude of this peak was greatly reduced simply using the first pulse merging criteria.

Fortunately, it was possible to identify more pulse merging criteria after processing the data with the original pulse merging script. New regions are outlined in red in Figure 3-8 that show the new split pulse regions. It was possible to identify these smaller areas only after merging pulses which met the main criteria of Figure 3-6. It is important to note the difference in magnitude of the split pulse regions in Figures 3-6 and 3-8. In Figure 3-6, the darkest regions of the plots correspond to 700 entries and 500 entries for $Q_1$ and $Q_2$ respectively, whereas the darkest regions of the plots in Figure 3-8 correspond to 350 entries and 400 entries for $Q_1$ and $Q_2$. The split pulse regions outlined in Figure 3-6 are not present in Figure 3-8 because every pulse in that region was selected and merged with a neighboring pulse to create a new $\delta t$ distribution. The
final pulse merging criteria, combining the split regions in Figures 3-6 and 3-8, is as follows: a pair of pulses is merged into a single pulse

\[
\text{If } \delta t < 71 \text{ ns AND } (Q_1 < 0.5 \text{ PE OR } Q_2 < 0.25 \text{ PE}) \\
\text{Else if } \delta t < 13 \text{ ns AND } Q_1 < 0.8 \text{ PE} \\
\text{Else if } \delta t < 26 \text{ ns AND } Q_2 < 0.35 \text{ PE} \\
\text{Else if } \delta t < 16 \text{ ns AND } Q_2 < 0.65 \text{ PE} \\
\text{Else if } 63 \text{ ns} < \delta t < 400 \text{ ns AND } Q_2 < 0.25 \text{ PE}
\]

Otherwise, those pulses are not merged. The pulse merging script accepts an I3RecoPulseSeries as input, and saves the merged pulses in a new I3RecoPulseSeries. The new pulse series is then appended to a new pulse map (which maps OMKeys to I3RecoPulses). This pulse map is then saved in a frame where it can be accessed by any existing IceCube software that accepts I3RecoPulseSeries as input.

The final results of the pulse merging script can be found in Figure 3-9 and 3-10 and 3-11.
Figure 3-9 Q vs. $\log_{10}(\delta t/\text{sec})$ distributions for $Q_1$ (left) and $Q_2$ (right) after pulse merging.

Figure 3-10 Final $\log_{10}(\delta t/\text{sec})$ distribution after pulse merging.
Figures 3-9, 3-10, and 3-11 show the results of the pulse merging script on a series of ATWD SPE pulses. Figure 3-9 shows that, after pulse-merging, the charge vs $\log_{10}(\delta t/\text{sec})$ distribution for both pulses is distributed about $\sim Q = 1$ PE and about $\sim \delta t = 10^{-6}$ seconds. All visible regions of split pulses seem to have been merged. Figure 3-10 shows the final $\log_{10}(\delta t/\text{sec})$ distribution after pulse merging. The large peak around $\delta t = 10$ ns has been removed from the distribution, leaving a much smoother curve. Figure 3-11 shows the final pulse charge distribution after pulse merging. This distribution has a mean of 1.014 PE and a standard deviation of 0.4497 PE; these values agree very well with the expected SPE pulse charge distribution.

![Figure 3-11: The final pulse charge (measured in PEs) distribution after pulse merging.](image)
3.6 Results

The net results of the previously described processing scripts are described in table 3-1.

<table>
<thead>
<tr>
<th>Process</th>
<th>Input Data</th>
<th>% passed</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT Selection</td>
<td>FRT frames (04/01-10/2013)</td>
<td>10.13 %</td>
</tr>
<tr>
<td>Pulse Merging</td>
<td>RT Selected pulses</td>
<td>96.33 %</td>
</tr>
<tr>
<td>HLC Criteria</td>
<td>Merged Pulses</td>
<td>0.35 %</td>
</tr>
</tbody>
</table>

Table 3-1

These processes were run on an initial data set containing FRT frames from runs 122127 through 122165—a total of 23476 FRT frames. Because only the first 5 ms of each FRT frame were used in this analysis, this data set contained 117.38 seconds of data.

The following chapter will discuss the creation of a full noise profile for the IceCube detector using the above results combined with the results obtained using HitSpool data. Parameterizations of the \( \log_{10}(\delta t/sec) \) distribution will also be discussed along with the possible improvement of IceCube’s current noise simulation methods.
Chapter 4

Extending IceCube’s Noise Parameterization

This chapter presents an improved noise parameterization made possible by the data extracted using the methods described in Chapter 3. Having successfully surpassed the low-\(\delta t\) limitation imposed by the HitSpool data format, this parameterization can be used to improve the existing IceCube noise simulation algorithm.

4.1 IceCube Noise Profile

Figure 4-1 shows a \(\log_{10}(\delta t/\text{sec})\) distribution combining HitSpool data (see Section 2.3) and low-\(\delta t\) Fixed Rate Trigger data (see Chapter 3).

![Log10(\delta t/sec) profile including HitSpool and FRT data.](image)

To create this plot, 117.38 seconds of HitSpool data were extracted from the 1060-second data set used in (Larson, 2013). The HitSpool data was then normalized according to the fraction of FRT...
data which passed the processing scripts—approximately 0.035% of the original sample (see Section 3.6). Both histograms in Figure 4-1 represent the summed $\delta t$ distributions of all DOMs in IC86.

The sharp drop in the FRT data corresponding to $\log_{10}(\delta t/\text{sec}) = -5.19$ is not a physical feature of IceCube low-$\delta t$ noise, rather it is a feature created by the single DOM distributions that were added to create the distribution shown in Figure 4-1. It is very unlikely that a single DOM would record two HLC events in a single FRT window, so the longest $\delta t$ interval that is likely to be measured on a single DOM is 6.4 $\mu$s (corresponding to a full readout of the FADC channel and both ATWD channels), or equivalently, $\log_{10}(\delta t/\text{sec}) = -5.19$. Fortunately, because HitSpool data offers accurate measurements of correlated noise for $\delta t$ as low as 2 $\mu$s, it is possible to extend IceCube’s current noise parameterization without encountering a discontinuity in the data. However, because of the HLC readout’s 6.4 $\mu$s limitation, there is a statistical bias against larger intervals in the FRT sample. If the first photoelectron pulse in the interval is not the first pulse in the readout window, then only a fraction of the readout is available. This creates a bias toward low-$\delta t$ pulses, and is the source of disagreement between the FRT and HitSpool data between -6 and -5 in Figure 4-1. The following section presents a possible parameterization for the full IceCube noise profile.

4.2 Suggested Noise Parameterization

The existing noise model for IceCube has been described in Section 2.4. Figures 4-2 and 4-3 present a possible continuation of the existing noise model to the low-$\delta t$ region.
A suggested noise model for IceCube. The afterpulsing peak has been modeled by a Gaussian distribution; the thermal component has been modeled by a Poisson process, and the correlated component has been modeled by a log-normal distribution. The "long timescale correlated" component is a residual distribution computed by calculating the difference between the data and the 3 other models. The details of these distributions can be found in the text.

The sum of all of the fits from Figure 4-2 displayed with the original data.
In previous IceCube noise simulations, the thermal noise component has been modeled as a Poisson process, the correlated noise component as a truncated log-normal distribution (Larson, 2013), and the afterpulsing component as a Gaussian distribution (Ma et al., 2009). These distributions are present in Figure 4-2 as the dark blue line, the red line, and the light blue line respectively. The continuation of the log-normal distribution to \( \log_{10}(\delta t/sec) = -9 \) agrees well with the data and may present a possible model for future IceCube simulations. The “long timescale correlated” component of Figure 4-2 was generated by computing the difference between the data and the sum of the other components. Its smoothness suggests that “long timescale correlated” noise might be well approximated by a closed-form expression. However, at the moment, there is no physical description of the noise occurring on this timescale—further study is needed to determine if it is correlated in some way to the events we have observed in the detector, or if there exists an unidentified source of noise.

Parameters used to generate the distributions in Figure 4-2 are shown in Table 4-1.

<table>
<thead>
<tr>
<th>Noise component</th>
<th>Distribution</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Afterpulse</td>
<td>Gaussian</td>
<td>( \mu = 6 \mu s ) &lt;br&gt;( \sigma = 2 \mu s )</td>
</tr>
<tr>
<td>Correlated</td>
<td>Log-normal</td>
<td>( \mu = -6 \left[ \log_{10}(\delta t/sec) \right] ) &lt;br&gt;( \sigma = 0.848 \left[ \log_{10}(\delta t/sec) \right] )</td>
</tr>
<tr>
<td>Thermal</td>
<td>Poisson</td>
<td>( \lambda = 220 \text{ Hz} )</td>
</tr>
<tr>
<td>Long Timescale Correlated</td>
<td>Data and other components subtracted</td>
<td></td>
</tr>
</tbody>
</table>

Table 4-1
Chapter 5
Summary and Outlook

This thesis has shown the methods by which a low-\(\delta t\) noise sample might be extracted from IceCube Fixed Rate Trigger data. Approximately 10.13\% of all FRT pulses were found to have precisely 1 neighboring pulse within 300 m and 5 \(\mu s\). Of these pulses, approximately 3.67\% were found to be erroneously split by the WaveDeform module. After these split pulses were merged, approximately 0.35\% of the merged pulses were found to be HLC, and contain high enough timing precision to produce a \(\log_{10}(\delta t/sec)\) plot with time separations on the order of nanoseconds.

By the methods described in Chapter 3, enough low-\(\delta t\) noise has been isolated to suggest a noise parameterization that could be used in future IceCube noise simulations. Correlated noise was found to be well-approximated by a log-normal distribution with a mean of -6 and a standard deviation of 0.848 (in units of \(\log_{10}(\delta t/sec)\)). The thermal noise component was well-approximated by a Poisson process with a rate of 220 Hz, and the afterpulse component was fit with a Gaussian distribution with a mean of 6 \(\mu s\) and a standard deviation of 2 \(\mu s\). Finally, a 4th distribution was identified and has been called “long timescale correlated” noise. At the moment, no closed-form expression has been used to fit this component. Further studies are needed to determine the origin and best fit for this noise.

Before a new simulation model can be implemented, parameters for the timing distributions must be determined for each DOM individually—DOM-to-DOM variations have not yet been determined for the correlated noise model. Individual DOM parameterization is currently ongoing for HitSpool data, but more data is needed to compute individual DOM
parameterizations for low-\(\delta t\) noise. This work will ultimately improve background rejection for all low-energy events in IceCube—particularly in PINGU as the collaboration seeks to observe single-GeV scale neutrinos.
Appendix A

4-parameter fit for low-\(\delta t\) FRT Study

The following plot shows a 4\textsuperscript{th} degree polynomial parameterization of the FRT study data.

![Graph showing a 4\textsuperscript{th} degree polynomial fit for FRT study data.](image)

Figure A-1: \(\log_{10}(\delta t/\text{sec})\) distribution for data collected in the FRT study, fitted with a 4\textsuperscript{th} degree polynomial.

In the event that only low-\(\delta t\) noise needs to be characterized, this 4\textsuperscript{th} degree polynomial offers a more accurate fit than the log-normal distribution described in Section 4.2. However, the fit is less robust and also simulates the sharp decline above \(\log_{10}(\delta t/\text{sec}) = -6\), which is not thought to be a feature of this data but, rather, a limitation of the IceCube digitizers.
ABBREVIATIONS


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September 2012
Julia Smith Scholarship
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Quasicrystal Structure Research Group
Advisor: Professor Renee Diehl, Penn State University
May 2011-April 2012

Professional Presentations

“NISXW study of Si adsorbed on an Al-Co-Ni quasicrystal,” APS March Meeting 2013.
Baltimore, MD, March 2013

University Park, PA, August 2012

Peer-Reviewed Publications

Note: Due to the scope and complex nature of modern particle physics and particle astrophysics experiments, the experiments are carried out by large collaborations of physicists. Articles published in refereed journals describing the results of these experiments appear under the names of all members of the collaboration in alphabetical order, and all authors are considered to share equal recognition for the results.


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