Analysis Proposal

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December 23, 2013

1 Detector Stability

Analysis of the detector stability using of partial detectors, 40-string though 79-string configuration, in [?] and [?] showed that there was significant rise in noise that could be attributed to the recently deployed strings and the on going freeze-in process. For the full detector, the same effect is seen, see Figure ??. The freeze-in process had an significant effect on the first half of the first full year of data taking, see Figure ??. As the freeze-in process subsides, the annular modulation of the muon rate with temperature, see Figure ??, causes the detector rate to have a sinusoidal-like time dependence. This becomes the most significant contribution to detector instability over time.

Figure ?? also reveals a continual decay in the detector rate throughout the operation of the full detector configuration. Comparison of supernova scaler rate for the 86-string configuration for strings deployed at all the different construction cycles, see Figure ??, shows that the decay is on-going even several years after deployment. Similarly, the freeze-in progresses has a depth dependence the, see Figure ??. The origin of this decay is unknown. There are multiple possible explanations that can be examined from the data:

- Construction effects: Continuation of the freeze-in process
- Detector effects: Detector aging and drift of detector settings away from optimal values

The freeze-in process continues even after the ice appears to be solid, as shown by the “Swedish Camera”, a camera system deployed in the deep ice at the end of String 80. Recordings from the “Swedish Camera”, see Figure ??, have shown that the ice surrounding the bore hole continues to change over the years. The air and particles trapped in the ice from drilling and refilling the bore holes are being pressed into a central column. This processes appears to be on-going and may cause low levels of triboluminescence similar to those associated with the solidification process that are seen as a decay in the supernova scaler, see Figure ??.

To establish the decay rate for the individual DOMs, a fit of a decaying exponential:

$$R(t) = A + B \times \exp\left(-\tau t\right) \tag{1}$$

is needed to the scaler data. The sinusoidal-like effect of the atmospheric muons has to be removed before such a fit can be produced. The IceCube trigger-level data has a significantly higher energy threshold and lower rate than the scaler data, i.e. $\approx 2100\,\mathrm{Hz}$ versus $\approx 5200\,\mathrm{Hz}$. To estimate the atmospheric muon effect with a lower energy threshold, the HLC rate for individual DOMs from the pDAQ log-files is extracted. The pDAQ log-files show a HLC rate of $\mathcal{O}(10\,\mathrm{Hz})$. This HLC rate mimics the effect of the atmospheric muons, as only two effects can set off the HLC condition: noise triggers on adjacent DOMs or by-passing muons. The coincidence rate, R_C, between two DOMs, assuming a noise rate of 500 Hz for each DOM, is given by

$$\begin{aligned} R_C &= R_1 R_2 2\Delta t && (2)\\ &= (500\,\mathrm{Hz})(500\,\mathrm{Hz})(2\times 10^{-6}\,\mathrm{s}) && (3)\\ &= 0.5\,\mathrm{Hz} && (4) \end{aligned}$$

where R_1 is the rate of process 1, R_2 is the rate of process 2, and Δt is the possible time window which these two can overlap. The noise rate for each DOM can be estimated using the SLC rate and the SN scaler rate for each DOM. The coincidence rate to satisfy the HLC condition can be The remaining rate can be attributed to the effect of atmospheric muon.

The SN scalers have a lower energy threshold than HLC though as they are sensitive to individual hits. The rate of individual hits attributed to atmospheric muons has to estimated from simulation. The single hit rate in data can be estimated by simulating muons with a known spectrum and determining the per-DOM single hit and HLC rate. The per-DOM single hit rate can than be scaled according to the ratio of the per-DOM HLC rate between simulation and data.

Effects from detector aging would be hard to disentangle from difference in the DOM components between different revisions of the DOM hardware and possible freeze-in effects. Further long-term studies with the DOMs in the freezer at Physical Science Laboratory would be necessary.

A drift of detector settings away from optimal values should be detectable from changes in the time constant of supernova scaler decay rate between strings deployed at the different construction cycles and during physics run transitions, respectively. A drift away from optimal values should be detectable by a jump or sink in the supernova scaler during the run transition. A jump in the detector rate was found during the physics run transitions, see Figure **??**. This jump can be attributed to the addition of previously removed DOMs from the detector configuration. There are no jump or sinks in the rate for the strings in Figure **??** during run transition leading to the conclusion that the effect of the new calibration values in minimal.

2 Muon Background

Over the course of the last several years the frequency and supernova significance, ξ, of false supernova alerts has risen, see Figure **??**. In [**?**] it has been shown that atmospheric muons are main cause of false triggers and are correlated to the muon hit rate, see Figure **??**. The nature of these muons however was not explored. The rising significance of the alerts was initially attributed to increasing solar activity as the sun approached the maximum of the 11-year solar cycle, see Figure **??**, as the temperature of the upper atmosphere rises with increasing solar irradiation. The rise in the significances should not be significantly effected by these long-term effects to the flux or energy spectrum of the atmospheric muons, as the background region is defined over significantly shorter timespan than these effects. The question remains whether there are distinct features in these events that can be extracted from the information provided by the DAQ.

In [**?**] the Data Storage Tape (DST) data was used determine the muon hit rate from the SMT8 trigger rate and the nchannel of the triggers. This muon hit rate is shown to be correlated to the ξ as determined by the the supernova online analysis. There was however no consideration for other triggers, such as the *String Trigger* and the *Volume Trigger*. These triggers could help identify large muon events that cause false supernova triggers more readily. For this reason, a study of the correlation of trigger rates for SMT8, SMT3, Volume Trigger, and String Trigger with supernova false trigger will be performed. For the supernova false triggers with $\xi > 6$, the trigger rate for all triggers of interest will be determined from the Super Data Storage Tape (sDST). The sDST data contains all individual triggers and time stamps thereof. The DST data only contains a bitmask that accounts for the the presence of a trigger, but not a count. This will help in account for possible overlapping triggers and give a better picture of the timing distribution. In order to ensure proper comparison of the data, the same rolling window as used in the SNDAQ online analysis is applied to the sDST data. The data is than split into the background and signal region and comparison of the trigger rates, nchannel distributions, and direction of events will be performed.

Investigating other triggers will remove some of the shortcomings of the analysis in [**?**]:

- SMT8 rate of DST data does not reflect the real SMT8 rate
- SMT8 trigger does not consider any geometry information beyond the local coincidence (LC) condition
- Supernova scalers have a lower energy cutoff than SMT8, i.e. is SMT8 the best possible measure or is there a different trigger?

The DST does not contain all the trigger information, as overlapping triggers are compressed into a bitmask that only accounts for the the presence of a trigger, but not a count. SMT8 triggers can overlap because of their extended readout windows as required by the EventBuilder. The probability of overlap of two SMT8, assuming 2100 Hz trigger rate for SMT8 and a 10 μs readout overlap window, is $\approx 0.2\%$. This should have an minuscule effect on the correlation method. When looking at all possible triggers the overlap between different triggers approaches 1. Additional other triggers, mainly the *Volume Trigger*, have a much higher rate ($\approx$ 3300 Hz), which leads to a much higher possibility of overlap for these triggers.

The SMT8 trigger does not consider the geometry of the events and the detector beyond the geometry requirement of the local coincidence (LC) condition. The geometry and time span of a muon event are completely different than that for a supernova event. Individual muon events would only illuminate certain areas of the detector for $\mathcal{O}$(1 - 10 μs), while the supernova event illuminates the entirety of the detector over the course of $\mathcal{O}$(1 - 10 s). Looking at triggers that do have stricter geometric constrains may help identifying muon events. Also the *Volume Trigger*'s much higher rate may yield more information about lower energy muons that the supernova scalers are sensitive to, but not SMT8.

3 Ice Efficiency

The optical properties of the ice in which IceCube is embedded are not uniform throughout the detector. One of the main assumptions that goes into the supernova onlien analysis a uniform illumination of the ice by the interaction of supernova neutrinos. The different optical properties however will cause the ice to not be illuminated uniformly, as some DOMs will have greater sensitivity than others because the light from the products of supernova neutrino interactions can travel more readily through the ice.

From studying the ice properties versus depth for MeV-scale positrons, one can establish an efficiency factor for the ice surrounding the DOM. To do this, an average of the effective volume of the DOMs outside the dust layer is calculated for an IceCube. The DOMs in the dust layer are excluded from the average because of the poor optical properties of the ice and the artificical decrease of the average effectice volume this would produce. The ratio between the average and the effective volume for the DOM is defined as the ice efficiency parameter. The effective volume of the DeepCore DOMs has to adjusted from the higher quantum efficiency as this effect is already taken into account separately, but still be able to compensate for their different location inside the detector.

4 SNDAQ Changes

The likelihood used in the SNDAQ online analysis relies on assumption that the noise rate on a per DOM level is Gaussian distributed, i.e. that the noise is purely Poissonic in nature. The per-DOM noise rate over long time scales however is known to be log-normal distributed

$$f_X(x;\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}}\exp\left\{-\frac{1}{2}\left(\frac{ln(x)-\mu}{\sigma}\right)^2\right\} \tag{5}$$

where μ is the location parameter and σ is the scale parameter. Over a short time scales as used in the SNDAQ analysis, i.e. 11 minutes, the log-normal behavior can be approximated with a Gaussian

$$f_X(x;\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left\{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right\} \tag{6}$$

where μ is the mean and σ is the standard deviation or variance.

Given Gaussian behavior of the DOM noise, we can measure a collective increase rate of the detector, $\Delta\mu$, employing the likelihood

$$\mathcal{L}(\Delta\mu) = \prod_{i=1}^{N_{\mathrm{DOM}}} \frac{1}{\sigma_i\sqrt{2\pi}}\exp\left\{-\frac{1}{2}\left(\frac{r_i-(\mu_i+\epsilon_i\Delta\mu)}{\sigma_i}\right)^2\right\} \tag{7}$$

where r_i is the rate in the signal bin, μ_i and σ_i is the average rate and error on the average rate estimated from the background region. From maximizing the log-likelihood we can obtain an analytical form of $\Delta\mu$:

$$\Delta\mu = \sigma_{\Delta\mu} \sum_{i=1}^{N_{\mathrm{DOM}}} \frac{\epsilon_i}{\sigma_i}(r_i - \mu_i) \tag{8}$$

where

$$\sigma_{\Delta\mu} = \left(\sum_{i=1}^{N_{\mathrm{DOM}}} \frac{\epsilon_i^2}{\sigma_i^2} \right)^{-1} \tag{9}$$

The assumption of purely Poissonic noise however appears to break down to do the non-Poissnic nature of the muon background on a per-DOM basis. A possible solution for this is the use a likelihood based on a log-normal distribution:

$$\mathcal{L}(\Delta\mu) = \prod_{i=1}^{N_{\mathrm{DOM}}} \frac{1}{\sigma_i r_i \sqrt{2\pi}} \exp\left\{ -\frac{1}{2} \left(\frac{ln(r_i) - (\mu_i + \epsilon_i \Delta\mu)}{\sigma_i} \right)^2 \right\} \tag{10}$$

where

$$\mu_i = ln\left(\frac{m^2}{\sqrt{v + m^2}} \right) \tag{11}$$

and

$$\sigma_i = \sqrt{ln(1 + \frac{v}{m^2})} \tag{12}$$

m and v are the mean and variance of the data, respectively. This changes $\Delta\mu$, such that

$$\Delta\mu = \sigma_{\Delta\mu} \sum_{i=1}^{N_{\mathrm{DOM}}} \frac{\epsilon_i}{\sigma_i}(ln(r_i) - \mu_i) \tag{13}$$