Performance of the ARIANNA Neutrino Telescope Stations

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Abstract: A new generation of neutrino telescopes is being established with the use of low noise, low power and inexpensive radio detection technology. The ARIANNA telescope exploits such technology to measure the intense radio pulse emitted by neutrino induced charged particle showers in the Ross Ice Shelf of Antarctica. Four stations are currently installed in the ice and taking both environmental as well as radio pulse data. The stations run autonomously using both solar and wind power generators. Data is sent north via wireless Internet and satellite modem peripherals. The performance of the stations will be discussed, and first results from the in situ data will be presented. The effectiveness of the Ross Ice Shelf as a radio quiet environment will be examined and initial studies on the angular resolution of the telescope will be explored.

Keywords: icrc2013, ARIANNA, neutrino

1 Introduction

The ARIANNA neutrino telescope will extend the sensitivity to very high energy cosmic neutrinos over currently existing experiments by at least an order of magnitude. The telescope will observe neutrinos through the measurement of a very strong radio pulse emitted from the charged particle shower created by a neutrino collision. The radio pulse is generated by the coherent radiation of charged leptons in the shower, in a process known as the Askaryan effect [1].

To develop the instrumentation, deployment procedures, data acquisition and analysis efforts of the ARIANNA telescope, a pilot program known as the Hexagonal Radio Array (HRA) [2] is currently underway. Prototype HRA stations have been deployed at the ARIANNA experiment site on the Ross Ice Shelf in Antarctica during each austral summer since 2010 [3].

During the 2012-2013 austral campaign, three redesigned prototype stations were deployed [4]. These stations focused on lowering the power consumption, improving the power generation and on establishing a robust, autonomous data acquisition (DAQ) system with redundant communication capabilities. Some of these goals had been met by previous station designs. However, the decision to forsake a CPU in favor of an embedded microprocessor in the redesigned stations necessitated the development of new solutions. The design and performance of these redesigned stations is discussed in this paper.

2 Station Hardware

Each HRA station uses four log-periodic dipole array antennas (LPDAs) to pickup radio pulses. Signals from each LPDA travel through 6 m long, low resistance shielded cables and are then amplified by 60 dB before entering the DAQ. The signals are sampled at 1.92 GHz and digitized by an in-house designed chip [5]. Signals from each LPDA are digitized on separate chips.

Several mechanisms may be used to trigger the readout of the digitized signals. An external pulse may be supplied to directly to the DAQ to trigger readout, useful in calibration studies such as those discussed in Sect. 3.2. The on-board microprocessor may trigger a forced readout of the system, useful for obtaining a minimally-biased set of data. Finally, a user-controlled trigger condition may be met. The DAQ provides both high and low trigger thresholds on each channel, as well as a sophisticated waveform pattern matching mechanism. In addition, a time-coincidence between matched patterns on separate channels may also be required. The typical trigger required at least one sample on two or more channels to be above the high threshold.

Two redundant communication mechanisms are installed in each station in order to send diagnostic and readout data from the station to laboratories in the U.S. The first communication method uses a long range wireless modem to establish a direct, TCP-based connection over the internet. A wireless relay on Mt. Discovery provided by the NSF allows the stations to reach the internet connection provided by McMurdo. The wireless internet connection functioned reliably on each station during the austral summer. The connection failed with the setting of the sun and loss of power to the relay; the last internet connection by a station was made on April 25, 2013. The second communication method uses an Iridium satellite modem to send very small (around 300 byte) binary messages. The stations have used these short burst data messages to send both diagnostic data as well as portions of readout data. The satellite connection has functioned reliably on each station during the entire data taking season.

Each station is equipped with a local power system that provides power for both the data acquisition and communication peripherals. Power to the station is provided by two lithium batteries. During the austral summer, the batteries are charged by three solar panels: two 30 W and one 100 W panel. A wind turbine mounted above the solar panels provides the capability to charge the batteries when sunlight becomes scarce. The redesigned stations use up to 10 W when configured for waveform data taking, but may also be configured to run in a diagnostic data taking mode that uses less than 1 W. All of the redesigned stations have remained fully operational well past the austral sunset.

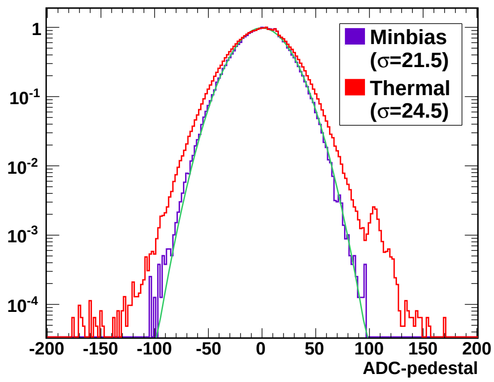

Figure 1: Distribution of the (sampled) waveform amplitude from one LPDA channel on the northern-most station. Randomly read out waveforms are shown by the purple, "minbias" line. Triggered event waveforms are shown by the red, "thermal" line. A Gaussian fit to the minbias data is shown by the green curve.

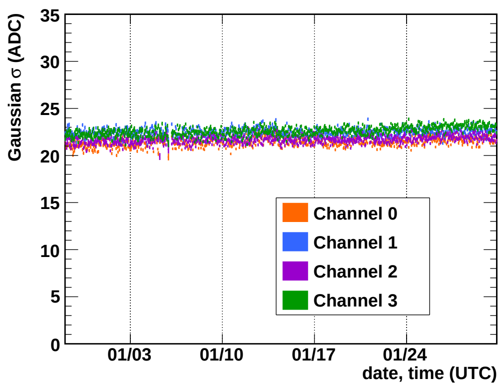

Figure 2: Width of the minbias triggered ADC distribution over the month of January. The width is consistent with noise from the station's amplifiers and its lack of variation reflects the radio quiet enviornment of the Ross Ice Shelf.

3 Data Taken In Situ

Analysis of data taken by the redesigned stations has been instrumental in establishing both the inherent angular resolution of the prototype stations as well as the suitability of the Ross Ice Shelf for the ARIANNA telescope as a radio-quiet environment.

3.1 Triggered Data

Data obtained from one LPDA channel of the northern-most station (Station 3), taken from January 10 to 13, 2013, is shown in Fig. 1. The amplitude of each sample of the readout waveforms is histogrammed for two different trigger requirements. The "minbias" histogram shows the distribution obtained from randomly read out, or forced triggered, waveforms. The Gaussian shape of this distribution indicates the lack of an external or internal radio noise source. The width of this distribution is consistent with the measured noise of the amplifier on this channel and is stable with time, as shown in Fig. 2. The larger width of the "thermal" distribution and the secondary peak at high amplitude reflects biases introduced by the trigger requirements. The thinness of the secondary peak arises due to the "single

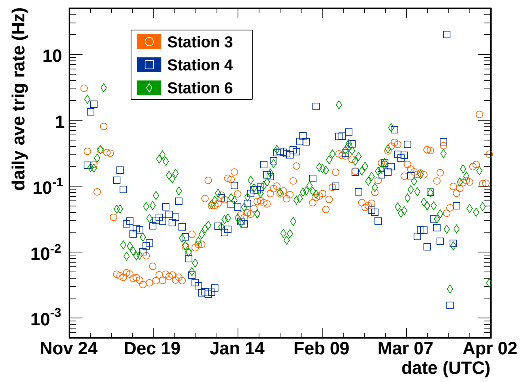

Figure 3: The average trigger rate of all redesigned stations in each 24-hour period since installation.

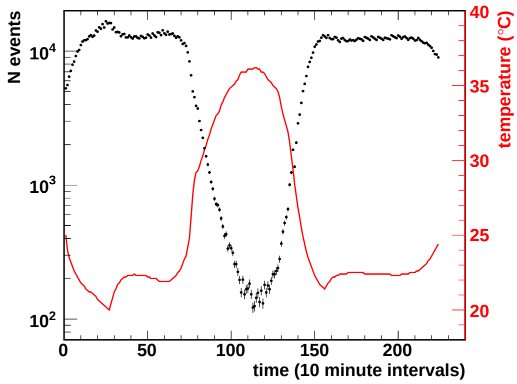

Figure 4: The number of events triggered on amplifier noise together with the ambient temperature, as observed in rooftop experiments at UC Irvine. The black points and left vertical axis indicate the number of triggers taken in 10 minute intervals. The red line and right vertical axis indicate the environment temperature.

high sample" trigger requirement in combination with a DAQ system that had not been fully calibrated. This effect is now well understood and will be eliminated by improved calibration procedures in future deployments.

The daily average trigger rate of each redesigned station is shown in Fig. 3. Until late March, the average rate is calculated by simply counting events in 24-hour bins. During this period, the stations were able to send all data north via the wireless internet connection. As this connection failed, diagnostic data from the station was transferred over the short burst satellite connection. This diagnostic data included the triggering rate of the station.

The rate fluctuations seen in Fig. 3 are well understood and do not lead to the loss of neutrino sensitivity. Each station is capable of recording hundreds of events per second, however the stations are throttled (currently up to 20 Hz) in order to prevent the local station data storage from being filled. Thresholds are adjusted remotely in order to bring the average rate to around 0.1 Hz. The thresholds required to do this are about 5 times the RMS of the amplifier noise and are low enough to trigger on neutrino pulses [6].

Figure 4 shows the anti-correlation between thermal trigger rate and station temperature. This data was taken by placing a station on a rooftop at UC Irvine. The station

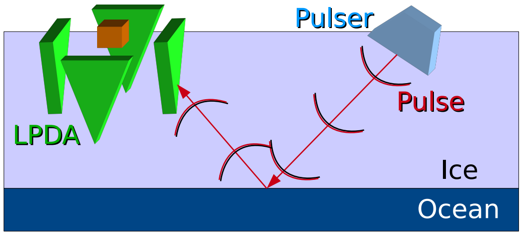

Figure 5: Illustration of a calibration pulse test. The radio pulse is emitted at the surface, reflects off the ice/water interface and propagates back to the surface, where it is picked up by the LPDAs at the station.

triggered only on amplifier noise; no LPDA antennas were connected. The anti-correlation may be somewhat counter-intuitive, as it is reasonable to believe that with higher temperature, the RMS of amplifier noise would increase. However, it is observed that this effect is very small. Instead, the DAQ electronics controlling the absolute trigger level are affected by temperature. This can lead to large variations in the thermal trigger rates, as the probability of a single sample to be above threshold is a very steeply falling function, as shown in Fig. 1. It does not, however, affect the neutrino sensitivity, both because temperature variations in Antarctica are generally slow and easy to adjust for, and because the changes in the thresholds are on the order of only a few mV.

3.2 Calibration Pulse Data

The ability of the station to measure a neutrino-like pulse has been explored using a dedicated calibration data set. For this calibration, a very short duration, about 1 ns FWHM, polarized radio pulse is fired down through the Ross Ice Shelf where it bounces off the sea water surface below and is measured by an HRA station, as shown in Fig. 5. ARIANNA is most sensitive to such reflected pulses, resulting from down-going neutrinos. The polarized radio pulse is generated by a Pockel cell driver and emitted from a Seavey horn, [7] referred to as the "pulser".

As the generated pulses are of quite large amplitude, a very small component of the pulse may reflect in the firn and be detected by the station, prior to the main reflected pulse. Due to this effect, the stations are not set to trigger directly on the pulse, as doing so would result in reading out the early pulse. Instead, an external trigger is timed to the main reflected pulse and sent directly to the DAQ. This removes any possibility of triggering on the early back-scatter and having the main reflected pulse arrive while the station is reading out. The early back-scatter effect will not be present for neutrinos interacting inside the ice below the firn, but may serve as an additional veto of very rare, ultra high energy cosmic rays that are capable of reaching the ice and generating an Askaryan pulse.

The location at which the pulse is emitted is varied, as is the relative polarization between the pulse and the LPDAs. First, several sets of data were taken with the pulse emitted directly at the station location. One of these sets is used as a reference in order to determine and calibrate away any inherent delays between LPDA channels. For a given LPDA channel, the signal measured in this reference, "near" data set is compared to the signal measured in a different orientation, for example, with the pulse emitted about 150 m

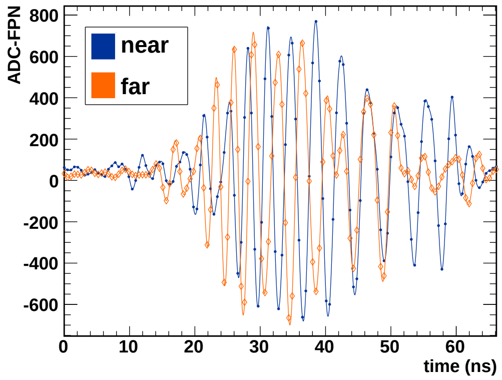

Figure 6: Comparison of two waveforms on one LPDA channel. The blue, "near" line with closed points shows the waveform recorded with the pulse generated at the station. The orange, "far" line with open points shows the waveform recorded with the pulse generated about 150 m from the station.

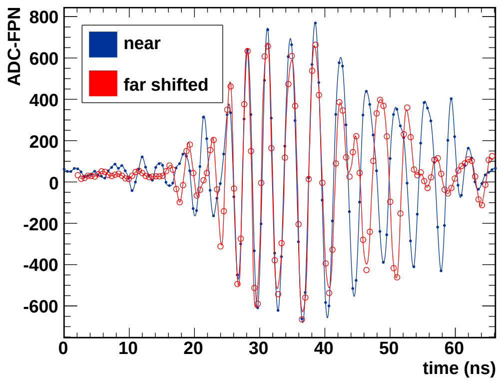

Figure 7: Comparison of the two waveforms from Fig. 6 after matching by shifting in time.

from the station, to the East. An example of such signals is presented in Fig. 6.

The pulse emission source is reconstructed by the following procedure. First, a correlation function between the two waveforms is constructed by shifting the "far" waveform with respect to the reference ("near") by some amount of time and calculating the Pearson correlation coefficient for the given shift value. This discrete correlation function is fit with a third-degree polynomial spline function to obtain a continuous correlation function. The two waveforms from Fig. 6 are shown in Fig. 7 after shifting the "far" waveform by an amount that maximizes the correlation.

The correlation functions for all four LPDA channels are then used to determine the direction from which it is most likely that a plane-wave pulse would have originated and produced the observed waveforms. For a given plane-wave source direction, the expected time differences between LPDA channels is calculated. The likelihood that these expected time differences are consistent with the measured waveforms is calculated using the correlation functions described above. The most likely source direction is determined by minimizing the negative logarithm of this likelihood.

The fitted source orientation direction is then used to propagate a plane wave back through the 560 m layer of

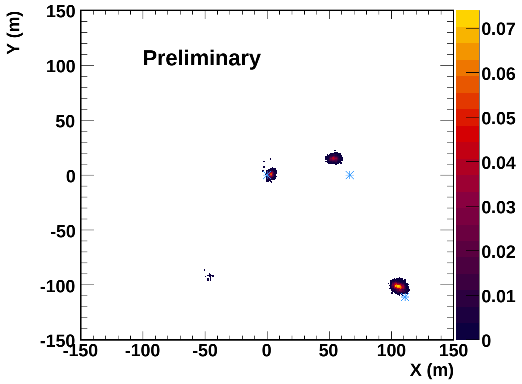

Figure 8: The reconstructed surface position of the pulse emission in several different signal calibration studies. Blue stars indicate an estimation of the true emission position.

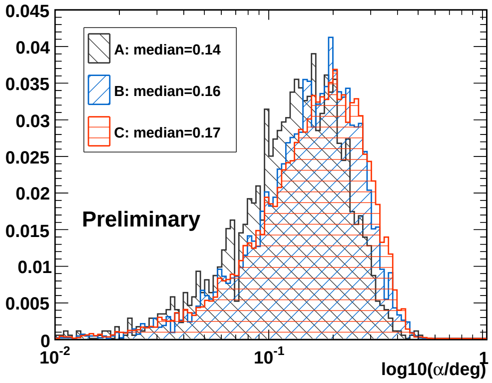

Figure 9: The angular difference, α, between the reconstructed source position of an event and the average reconstruction position for that pulser-station orientation. The results for several different pulser orientations are shown.

ice. The plane wave is tracked down through the ice, is reflected off the sea water and is tracked until it reaches the surface, which is taken to be the reconstructed pulser source position. A simple ice model is used, in which it is assumed that the index of refraction of ice varies linearly in the 50 m firn layer from 1.33 at the surface to 1.78 in the ice. The reconstructed pulser position is shown in Fig. 8 for several different orientations. Blue stars in this figure show a rough estimate of where the pulse emission occurred. This location is not known to better than 10 m. Note that effects such as the relative spatial position and orientation of each LPDA have not been taken into account, so the absolute pointing accuracy of the station has not yet been studied.

However, the inherent angular precision with which the station can reconstruct the source of a pulse has been quantified using these studies. Figure 9 shows the distribution of the angular difference between a reconstructed event and the average reconstructed position of that particular pulser orientation, for several different orientations. The angular precision is about 0.17° even with the simple reconstruction procedure described above. This indicates that the full ARIANNA telescope should be able to reach theoretical angular resolution limits for neutrino signals. [6, 8]

4 Conclusions

Three redesigned HRA stations have been deployed [4] in the Ross Ice Shelf of Antarctica, as prototypes stations of the full ARIANNA telescope. The stations have operated reliably well past the austral summer. The stations are equipped with redundant communication peripherals that allows diagnostic and waveform data to be sent north.

Analysis of this in-situ data has demonstrated that the Ross Ice Shelf provides a radio quiet environment. While triggering rates on the stations have been observed to depend on temperature, the effect is understood and easy to compensate for. Desired trigger rates have been obtained with relatively low trigger thresholds.

A set of signal calibration studies have been performed by bouncing very short duration pulses off the ice/water interface below the station. A preliminary reconstruction analysis of these studies yields an inherent angular precision of about 0.17°.

In the coming 2013-2014 austral campaign, the full 7 station hexagon of the HRA will be completed. The deployed stations will be similar to those described in this paper. Improvements will include a more complete and precise calibration of the data acquisition systems, extended protection from potential sources of internal noise and enhancements to the station communication software.

Further discussion of the ARIANNA experiment, including the expected sensitivity of the full ARIANNA array and a first look for neutrino signals in the HRA data may be found in these proceedings. [4]

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