PROCEEDINGS OF SCIENCE

Enhanced Ultra-High Energy Neutrino Search at the Askaryan Radio Array using Template-based Techniques

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The Askaryan Radio Array (ARA) is a gigaton-size neutrino radio telescope situated near the geographic South Pole, which has been in operation since 2011. It is specifically designed to detect Askaryan emissions resulting from the interaction between ultra-high energy neutrinos (> 10 PeV) and Antarctic ice. Each of the five ARA stations is equipped with 16 antenna clusters arranged in a matrix configuration, approximately ~200 m deep in the ice. In this analysis, we utilize data from two ARA stations with a total livetime of ~10.5 years, representing a two times increase in exposure time compared to the previous ARA result. To enhance the detection of neutrinos at the ARA, we introduce the template method known as a matched filter, which was inspired by the Laser Interferometer Gravitational-Wave Observatory (LIGO). This method entails the direct comparison of data with simulated neutrino templates, facilitating the identification of low signal-to-noise ratio (SNR) neutrino signatures, ultimately resulting in an improved low energy threshold. Our study presents the diffuse neutrino search results derived from the analysis of data, with an estimated factor of 4 sensitivity improvements above 10 PeV. These improvements were achieved through a factor of 2.3 from the application of the simulated template technique and a factor of 1.7 from increased livetime.

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1. Introduction

Ultra-High Energy Cosmic Rays (UHECRs) have been theorized to be produced from cosmic accelerators and observed by large telescopes like the Telescope Array (TA) and Pierre Auger Observatory [1, 2]. However, the origin of UHECRs remains a mystery. One promising way to understand the acceleration and propagation mechanisms of UHECRs is by detecting ultra-high energy (UHE) neutrinos that result from the interaction between UHECRs and Cosmic Microwave Background (CMB) photons, known as the Greisen-Zatsepin-Kuzmin (GZK) suppression [3, 4]. The cosmogenic or GZK neutrinos produced from this interaction can provide insights into understanding UHECRs, such as their propagation mechanisms and mass composition [6].

Detection of UHE neutrinos has been a significant challenge, primarily due to their low interaction cross-section [7], resulting in an event rate of approximately one event per gigaton per year for UHE neutrinos. With its large volume and radio transparency, the ice in Antarctica offers an ideal medium for constructing a detector capable of capturing UHE neutrinos.

When UHE neutrinos interact with the Antarctic ice, they produce electromagnetic cascades. The emitted Cherenkov radiation undergoes the Askaryan effect [8–10], creating coherent radio waves when the radiation wavelength is longer than the shower size. In the radio-transparent Antarctic ice, unlike optical light, coherent radio waves do not scatter and can have an attenuation length of ~1 km [11]. Thus, this characteristic allows the Askaryan Radio Array (ARA) to deploy each station, a cluster of antennas, in ~2 km distance with a hexagonal pattern.

In this proceeding, we present the results of the diffuse Neutrino search by analyzing data measured by the ARA detector. Additionally, estimate the detector's sensitivity through simulations and corresponding livetime calculations.

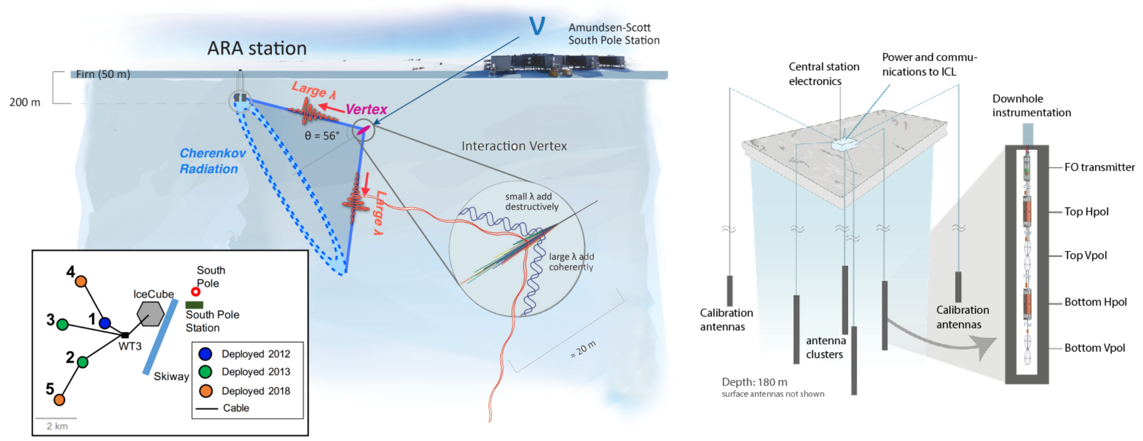

Figure 1: Left: Layout of the currently deployed ARA stations and a diagram of UHE neutrino interaction creates Cherenkov radiation and is observed by ARA. Right: The schematic of the individual ARA station design

2. ARA Detector

The ARA detector is a neutrino telescope located in the glacier ice near the South Pole. The primary objective of ARA is detecting UHE neutrinos with energies above $E_\nu > 10^{16}$ eV. The ARA detector consists of five autonomous stations deployed up to 200 meters below the Antarctic ice surface.

Each ARA station has 20 radio frequency (RF) antennas and corresponding electronics below the ice arranged in six strings. And a data acquisition (DAQ) system, designed to collect the measured data from the antenna, is located at the surface of the ice. The 16 antennas are deployed in a matrix configuration, enabling the observation of neutrino-induced radio signals with timing information for the vertex reconstruction. The remaining 4 antennas, deployed ~40 m far from the center of 16 antennas, are designed to transmit the known pulses for calibration purposes.

The RF antennas consist of two types: sensitive to vertically-polarized (VPol) signals and horizontally-polarized (HPol) signals. This polarization measurement allows for the determination of the electric field (E-field) polarization, which is crucial for reconstructing the direction of the neutrinos. Each antenna is capable to measured 150-850 MHz of RF range [12]. The schematic design of the ARA detector is illustrated in Figure 1.

2.1 Data Samples

This proceeding is focused on data measured from the second and third ARA stations (A2 and A3). Both A2 and A3 started taking data in 2013. Due to the limited access to the South Pole, data must be physically shipped to the outside for analysis. Hence, the available dataset when this analysis started is the data taken from A2 and A3 in the 2013 to 2020 period. The corresponding accumulated livetime of A2 is ~1989 days and A3 is ~1924 days, as shown in Figure 2. Over the course of eight years, total ~2 billion events were recorded between the two stations. The total data is categorized into 5 different configurations for A2 and 9 different configurations for A3 due to optimizing detector parameters, such as the number of active antennas and readout window sizes.

The progress of data analysis of all 5 stations is in [13].

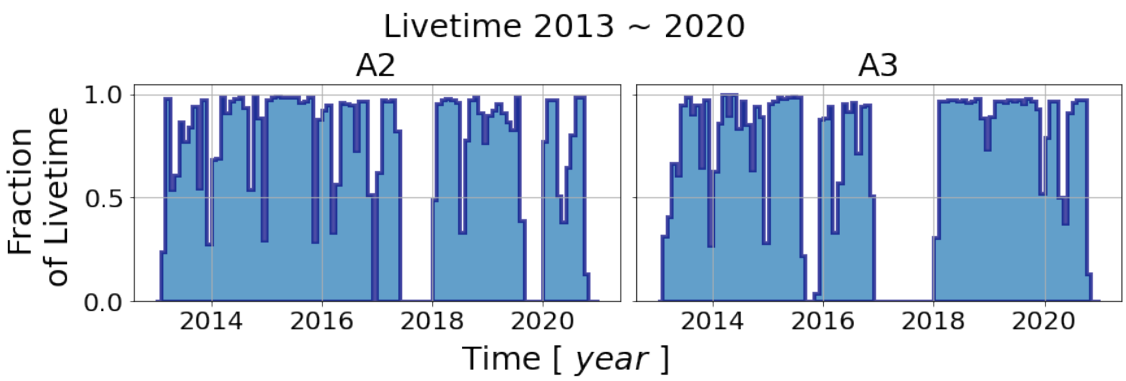

Figure 2: Fraction of live time of A2 and A3 in the 2013 to 2020 period

3. Simulation

The expected neutrino-induced signal that ARA can observe is simulated by AraSim [12]. The in-situ detector and antenna responses are implemented as a gain model in [15]. Based on this model, we generated thermal noise background that is expected from the ice at the South

Pole. It also incorporates an Askaryan radiation model by Alvarez-Muniz *et. al* [9], considering neutrino-induced signal, propagation in the ice.

The simulated neutrino event is based on all 3 neutrino flavors and the electromagnetic or hadronic shower models. The events are generated based on a power law spectrum with a flux proportional to the energy to the power of -1 from 10^{16} eV to 10^{21} eV. And neutrino direction and location of the vertex are uniformly distributed in the inside of ~12 km radius of the sphere when simulated ARA stations are located in the center. We simulated a total of 16 simulations by considering the number of stations and each configuration. Each event is weighted by survival and interaction probabilities. And later in the sensitivity calculation, we also implemented the neutrino flux model into the simulated event [6].

Figure 3 is the trigger-level of the effective area of each station by averaging all the configurations.

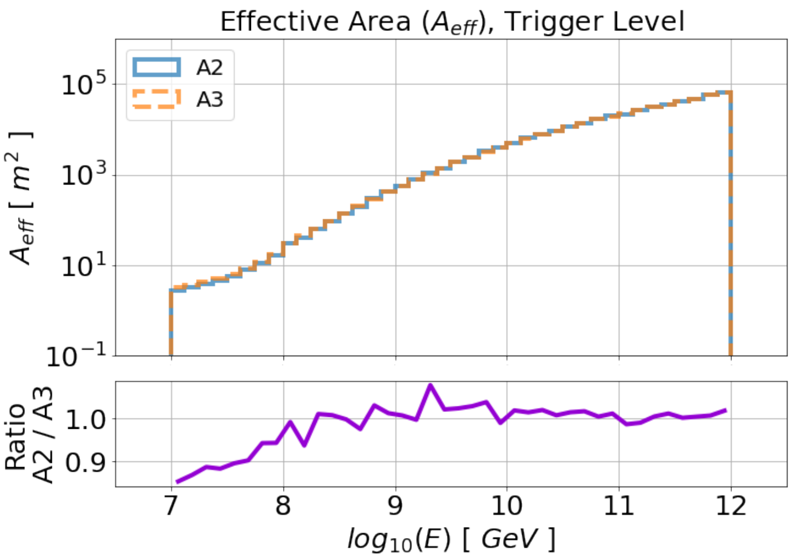

Figure 3: Top: The simulated trigger-level effective area for A2 and A3. Bottom: Differences between A2 and A3

4. Data Analysis

The analysis is conducted in a blinded technique, only using 10% of the randomly selected data (burn sample) to minimize bias toward the data and ensure the integrity of the results. By using this burn sample, we develop quality cuts that exclude known sources of background. After the implementation of quality cuts was performed, we applied an analysis cut that separates thermal noise and potential neutrino signal to calculate sensitivity.

4.1 Background Rejection

The background is removed in several levels of the quality cuts to effectively exclude anthropogenic and thermal noise.

The first level corresponds to the event that is contaminated by DAQ noise. Due to the fluctuation of the DAQ condition, the event recorded from ARA rarely observed harmonic oscillation of electronic. These kinds of events were removed by cross-checking secondary information, such as the amount of voltage that goes into the digitizer board and the temperature of DAQ. Additionally, we applied a band-pass filter outside of RF frequency range to suppress excess power produced by this DAQ fluctuation.

The second cut level corresponds to removing the continuous wave (CW) events. The major CW event consists of the communication signal from a weather balloon launch that happens twice every day at the South Pole. This communication signal corresponds to frequencies of ~410 MHz. To filter out this contamination signal from data, we applied a geometric filter [16].

The third cut is designed to exclude the digitizer board channels that experiencing dead-bit issues. In 2018, one of the digitizer boards in A3 caused the dead-bit issues and had to exclude from the analysis. In order to remove data, we check the ADC distribution of data, and if there is any gap in a certain bit, we exclude it from the analysis,

The fourth cut is designed to remove the calibration pulse smeared into data and the signal produced by surface activity at the South Pole. Both signals are removed by the interferometric technique [16]. We applied interferometry to a known calibration pulse event to estimate the calibration pulse position. And we applied the same method to all events to estimate the zenith angle cut that removes surface activity.

The Fifth cut is performed by using the matched filter technique [15, 17, 18]. The direct comparison between the neutrino template and data identifies the impulsive anthropogenic event that is not flagged from the fourth cut. The neutrino templates used in the matched filter method is also categorized by different zenith angle due to antenna angular gain differences. By matching different zenith-dependant neutrino templates, if the reconstructed vertex position by the matched filter is above the surface, we removed events.

The final cut corresponds to signal and background separation. At this step, we expect the remaining data to be most likely a thermal noise event or potential neutrino candidate. To separate the remaining background, we utilized interferometric and matched filter techniques. We optimized the final cut by making the diagonal cut in the 2d plane based on two parameters shown in Figure 4. We tested every parameter of the diagonal fit, which are slope and intercept, and chose the best parameter that shows the maximum ratio between the probability of having the neutrino signal among remaining background events by cut in 90% confidence level (CL) and the expected number of the neutrino events passed the cut by simulation results.

We performed all the background rejection steps into both A2 and A3 stations and all the configurations to estimate signal efficiencies and sensitivity.

4.2 Results

The detector efficiencies are estimated by applying the neutrino flux model as weight into simulated neutrino events that passed cut. To have a global sensitivity of the detector, when we merge each station and configuration results, we also applied corresponding live time. Based on the estimated sensitivity shown in Figure 4, we improved sensitivity compared to the previous analysis in the factor ~4. The increased live time is contributed to the factor ~1.7. And the final cut by interferometric and matched filter techniques mostly contributed to the factor ~2.3 improvement.

We could not estimate the uncertainty of background in the proceeding. This uncertainty will be evaluated in the future.

A more detailed description of the results will be updated in the final version of this proceeding.

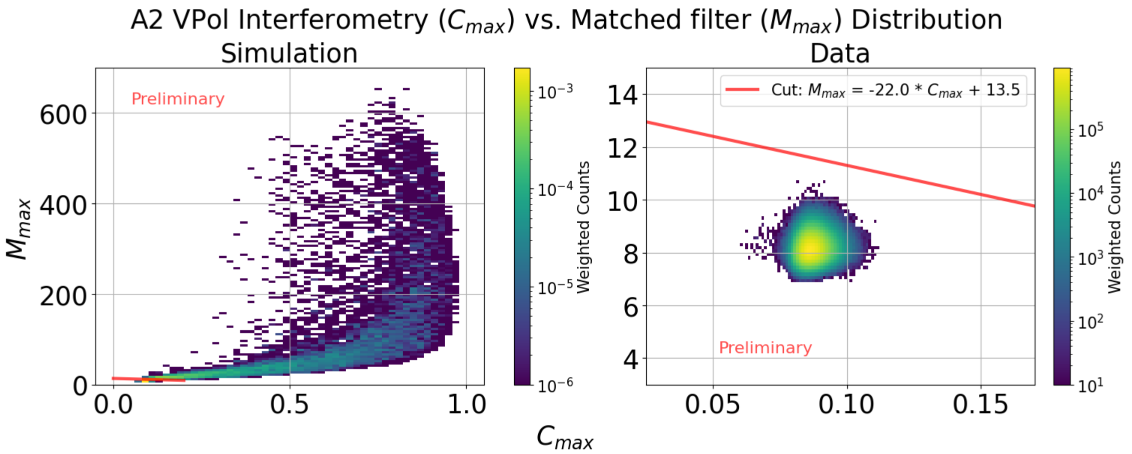

Figure 4: Left: The simulated neutrino signal distribution by following interferometric and matched filter parameters. Right: The distribution by same parameters by data from ARA

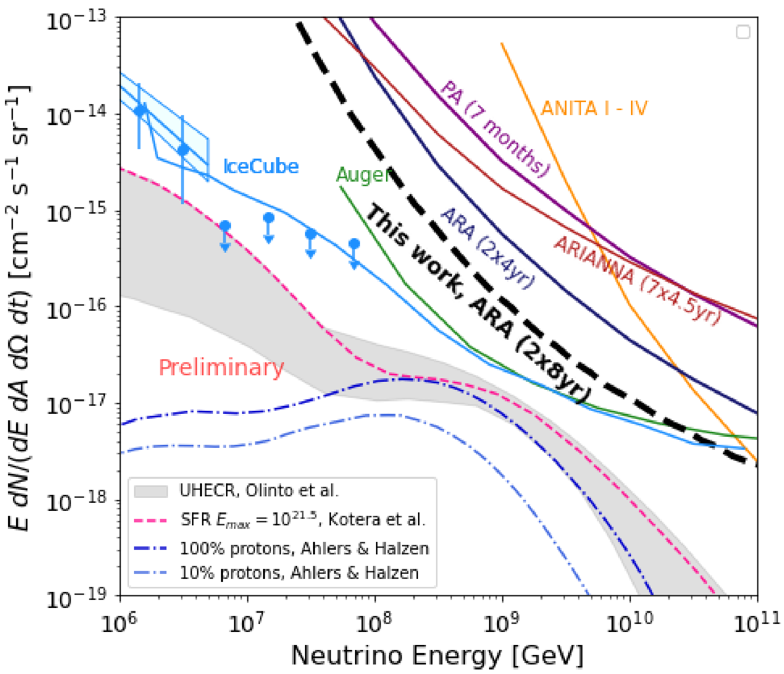

Figure 5

5. Conclusion

The continuous measurement by the ARA detector and implementation of matched filter method demonstrated improvement in the search for UHE neutrino signal. The matched filter method provides a valuable strategy for detecting low signal-to-noise ratio (SNR) signals in a radio detector. Also, a comprehensive understanding of the detector responses within the noise background is crucial for implementing the matched filter method effectively. In the near future, this analysis will be performed into 100% blinded data to search for the existence of a UHE neutrino signal.

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