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Optimization of an ARA like Radio Neutrino Detector in Ice

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Radio ice detectors for Ultra High Energy neutrinos take advantage of large natural ice sheets to detect the impulsive emission of radio signals from Askaryan emission. The Askaryan Radio Array (ARA) has deployed several prototype detectors at the South Pole. Using Monte Carlo simulations, we re-examine various design parameters of a neutrino detector at the South Pole. Along with the frequency acceptance of the detector, the sensitivity of an ARA-like detector depends on several parameters such as station depth, station horizontal baseline and geometry of the station. The effect of some of these parameters on sensitivity exhibit significant energy dependence. We also analyze the change in signal response of the station with different frequency acceptance bands which could help reduce the cost of the new upcoming stations.

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1. Introduction

The flux of cosmic rays has been observed from low energy up to the most energetic events near $10^{20}eV$. The origin and acceleration of these cosmic rays are still among the open questions in Astroparticle physics. Some of these questions can be answered by studying cosmogenic neutrinos, which are produced in the GZK process in which Ultra High Energy Cosmic Rays (UHECR)($E > 10^{18}eV$) interact with the cosmic microwave background resulting in high energy neutrinos.

However, the low flux of UHECR and small interaction cross-section of neutrinos make it extremely difficult to detect such neutrinos. One method of observing these neutrinos is to detect their broadband Askaryan radio emission[3] in ice using radio detectors. The estimated event rate for cosmogenic neutrinos is about $1/\text{km}^3/\text{yr}$, which demands a ground based detector covering $O(100km)$. Radio array detectors are also advantageous because of their cost-effectiveness.

Since the neutrino flux is extremely small, the design of such radio arrays must be optimized. Here, we take the Askaryan Radio Array (ARA) as benchmark and present the results of simulation of modified ARA baseline geometry with an eye towards potential improvements. The results indicate that a larger geometry with the same number of stations, improves the passing rate as well as the angular reconstruction of the station.

2. Simulation Details

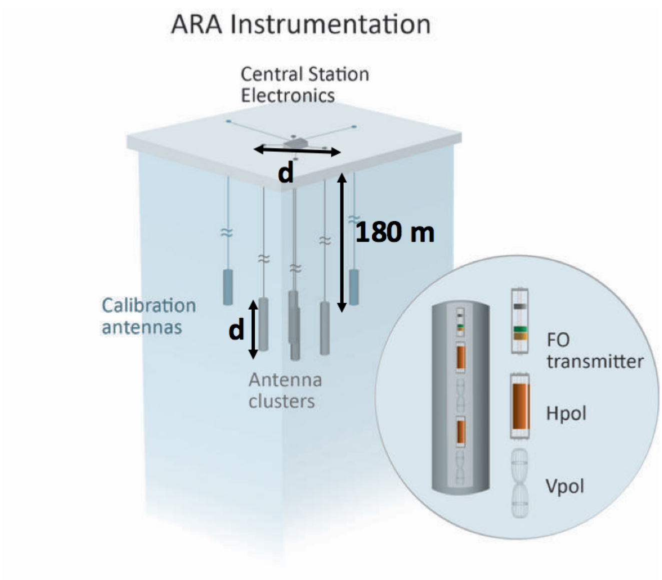


Figure 1: Overview of the ARA station. The distance **d** is the vertical distance between the top and bottom antenna on a string, and is also equal to the horizontal distance between the opposite strings. In this study, we are optimizing this distance **d**.

The current geometry of the ARA station is shown in Fig 1. The station sits 200 m deep in the antarctic ice with 2 pairs of Hpol-Vpol antennas on four strings. In the current configuration, the vertical distance between the top and the bottom antenna on the string (called baseline size **d** as shown the Fig 1) is 20 m, which is also the horizontal distance between the two opposite strings. In the study, we keep the bottom of the station fixed at 200 m which is motivated by drilling limits in ice, cost of drilling and the results of the study[9] which show that we see more ice volume as we go deeper. We then investigate the response of an ARA station when the baseline parameter is changed and compare the results for 4 distinct geometries of baseline size 20, 40, 60 and 80 meters.

To understand the antenna response, we need to discuss the two staged trigger of an ARA station. The first stage requires that for any antenna, the power, integrated over about 100 ns must exceed a settable multiple of the mean thermal background. This is called the L0 trigger or Level 0 trigger. The Level 1 or L1 trigger, is a multiplicity trigger, which requires that 3/8 antennas in either horizontal or vertical polarization must pass the first trigger stage in a time window set for casual signal crossings of the array (170 ns in the 20m baseline design). The time window depends directly on the geometry as described in section 2.1.

To simulate the geometry, we use Monte-Carlo simulation Package AraSim[4], which models signal generation, signal transportation and the detector response to generate data in the same format as real data. The simulations are performed with noise for energies ($> 10^{16}$ eV), with the global trigger as the L1 trigger.

2.1 Trigger Threshold Dependence on Station Size

The time frame in which the multiplicity trigger condition is checked, which is the maximum time taken by light to traverse the station, is given by

$$t = n * \sqrt{2} * d/3 \tag{2.1}$$

where n = 1.76, is the index of refraction of the ice and d is the baseline parameter as shown in Fig. 1. As we increase the baseline, the timing window increases. This means that the threshold must be properly adjusted as the increased timing window would result in increase of the accidental or thermal triggers.

To adjust the threshold, we note that the global trigger rate of the station is given by [5]

$$R_{global} = 2 * R_{(N,M)} \approx 2 * N * C_N^M * r^N * t^{N-1}; \quad C_N^M = \frac{M!}{N!(M-N)!} \tag{2.2}$$

where N is the multiplicity of the trigger (3 for ARA), M is the total number of channels of a given polarization, t is the timing window, r is the single channel trigger rate and $R_{(N,M)}$ is the trigger rate from one polarization. The factor 2 is to account for triggers from both horizontal and vertical polarization. Due to bandwidth constraints, the global trigger rate is chosen to be 5 Hz.

One can determine the single channel trigger rate (SCTR) from this equation for a given configuration of the station. As discussed above, SCTR depends on the threshold value. After calculating SCTR, a trigger threshold scan is performed on the AraSim noise waveform to find the threshold needed to obtain the corresponding rate. The numerical values for these parameters for various configurations are summarized in Table 1, where as Fig. 2 shows the variation of SCTR as a function of threshold (in units of noise sigma).

Baseline Size (m)	Timing Window (ns)	SCTR (KHz)	Power Threshold
20	166	8.15	6.463
40	332	5.13	7.727
60	498	3.92	6.88
80	664	3.23	6.99

Table 1: The minimum timing window, single channel trigger rates (for the 260K thermal plus electronics environment), and the power threshold (in sigma of thermal noise) for an overall L1 trigger rate of 5 Hz. Note that the current configuration of an ARA station has a baseline of 20 m.

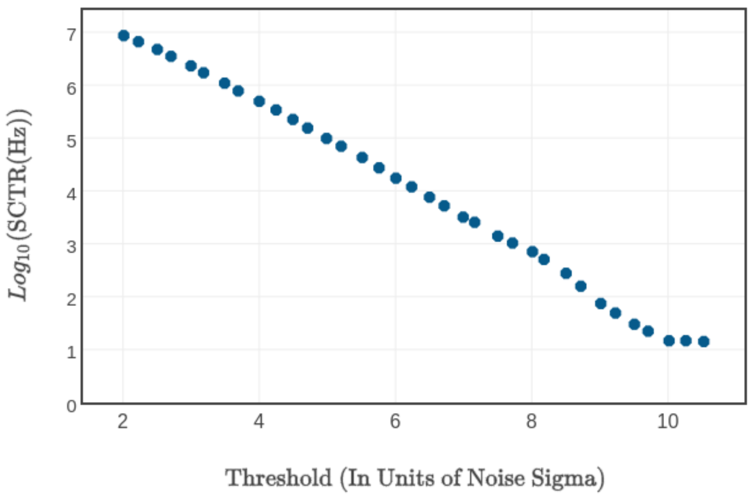


Figure 2: The single channel trigger rate is shown as a function of the power threshold.

3. Results

To analyze the generated Monte-Carlo data using AraSim, we use a Radiospline Interferometric Reconstruction[8] package which uses time delays in the antennas to compute cross-correlation and reconstructs the direction of the signal. The package uses ray-tracing for time delays and only includes the direct ray from the source, not the reflected ray[7]. Further, we also implement a quality filter in reconstruction called nchannel filter in which we demand that at least n channels pass the threshold for reconstruction. It should be noted that the threshold for a channel to be included in reconstruction is 5 σ of voltages, which is different from the L1 trigger.

3.1 Passing rate

In the simulations, 1 million neutrino events were generated in a large cylindrical volume in ice surrounding the station. Fig. 3 shows the variation of trigger efficiency with the baseline size of the station. Trigger efficiency here is defined as the ratio of number of events which pass the global

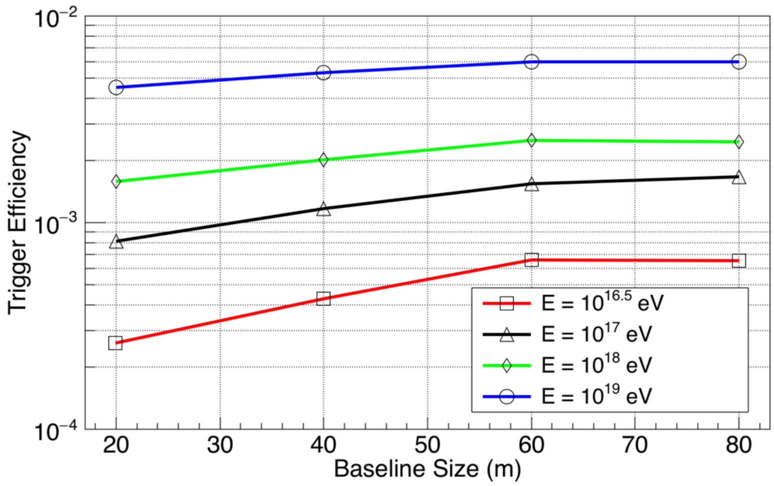
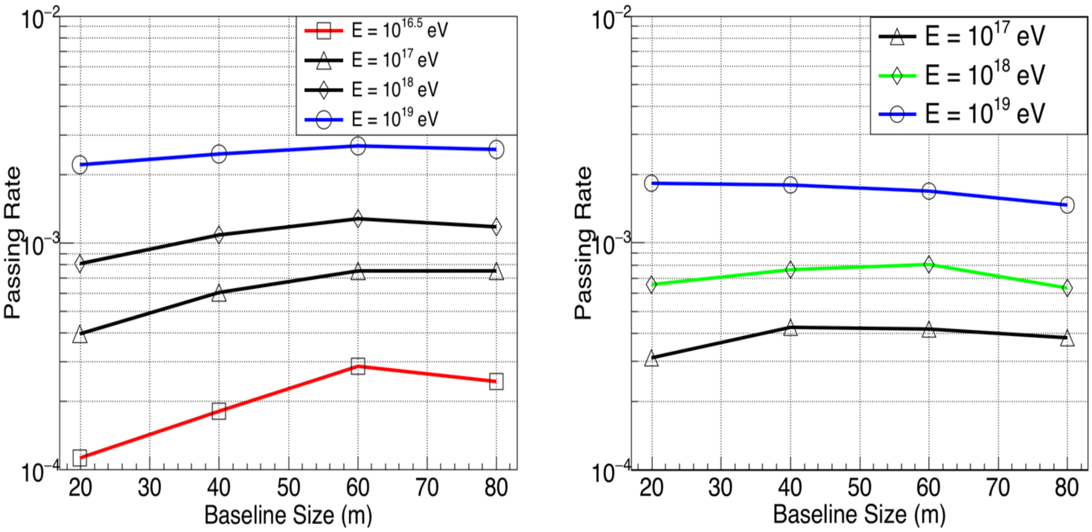


Figure 3: Behavior of trigger efficiency with baseline for different energies when the neutrino events are generated in the ice surrounding the station. Trigger efficiency is defined as the ratio of triggered events to the generated events.

trigger with the total number of thrown events. The error bars in these plots are less than the height of the marker, and hence have not been plotted.

After passing the simulated data through the reconstruction algorithm, we obtain the passing rate, which is defined as the ratio of number of reconstructed events(with the quality filter nchan ≥ 4) to the total number of simulated events. It is proportional to the neutrino effective area of the station. Here we are only interested in the relative change with station size. As shown in Fig. 4a, the passing rate increases as we increase the baseline size up to 60 m, and then becomes flat. This is because as we increase the baseline, the trigger efficiency increases, but the filter efficiency decreases for nchan ≥ 4 or higher, as shown in Fig. 6. The increase in number of triggered events can be understood by Fig. 5. The figure shows that for baseline of 20 m, the station is fully illuminated most of the times, whereas when we increase the baseline, we pick up more events but majority of the events only illuminate part of the station, which can still be used to successfully reconstruct neutrino events. Another important feature is that the gain is not significant at highest energies of 10^{19} eV. The main reason for this is that most of the higher energy events are farther away from the station, so the entire station lies in the Cerenkov cone, where as for the lower energy events, the events are closer to the station, and hence the trigger rate is affected by the geometry.

It is known that if the four channels going into reconstruction lie on the same plane, the angular position of the vertex may not be determined unambiguously, i.e. there is a degeneracy in one direction. To see the effect of such events, we plot the passing rate distribution with nchan ≥ 5 in Fig. 4b. This is a very conservative case in which at least one channel is not in the plane, which lifts the degeneracy. It is evident from the graph that passing rate still increases first and then decreases. This behavior can be understood by looking at Fig. 6. With nchan ≥ 5 we start loosing more events due to the filter than we gain in the trigger, which suggests that a station of size 40 m would be most suitable for neutrino searches. However, even for events with nchan=4 a successful zenith reconstruction - important for background rejection - can be obtained.



(a) Passing rate for nchan ≥ 4 (b) Passing rate for nchan ≥ 5

Figure 4: The passing rate is shown as a function of the baseline size for different energies. The passing rate is defined as the ratio of reconstructed events (with different nchannel filters) to the total number of simulated events.

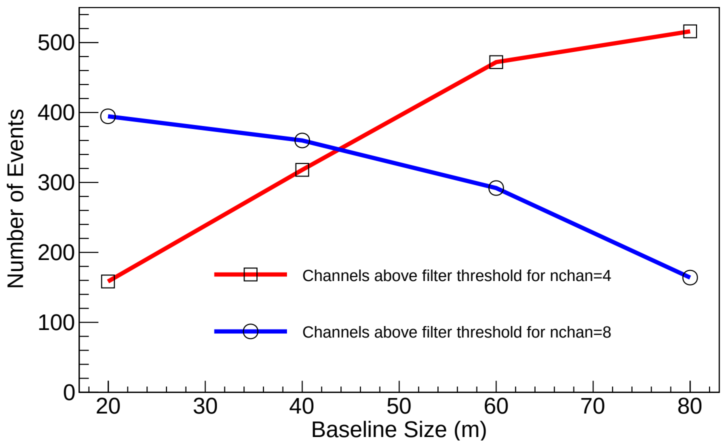


Figure 5: The number of events for two different filter conditions is plotted versus the baseline size of a station at 10^{18} eV. The filter conditions shown are events with exactly 4 or 8 channels that pass the threshold set for reconstruction.

It should be noted that the above results only include vertically polarized data, but a similar behavior was observed in the simulation with both Hpol and Vpol data.

3.2 Angular Resolution

Apart from the number of events, we also expect to see an improvement in the angular resolution of the detector as the arrival times are measured over larger baselines. Fig. 7 shows the azimuth

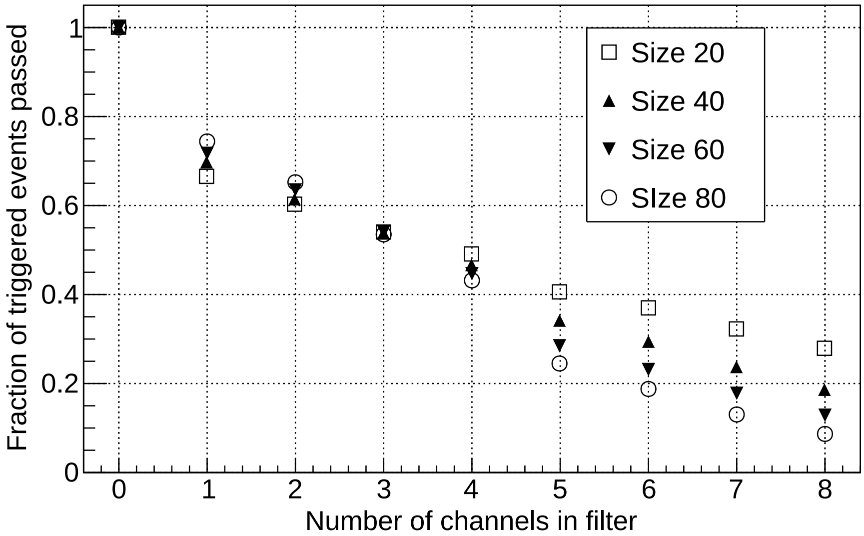


Figure 6: The cumulative nchannel distribution which shows the variation in filter efficiency (the fraction of events passing the n-channel filter) for different baselines at E= 10^{18} eV. The filter is defined as requiring *n* channels for reconstruction.

angular differences of reconstructed events for a station of size 40 m. We then define the median angular resolution as the angle that contains 50% of the events. The median angular resolution for different energies and station size is summarized in Table 2. Note that this reconstructed data here is with nchan ≥ 4 filter. Despite a slight reduction in the multiplicity of the number of channels, the angular resolution improves significantly with larger station size.

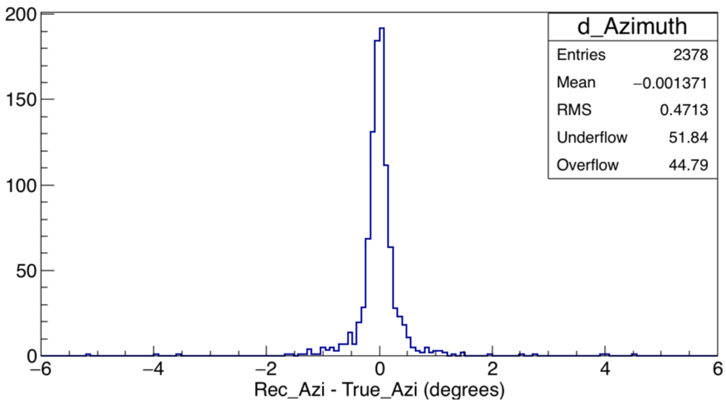


Figure 7: Reconstructed Azimuth - True Azimuth for an ARA station with baseline size 40 meters at 10^{18}eV. The reconstruction was performed using the Radiospline Interferometric Reconstruction package discussed earlier.

Energy (eV)	Size: 20 m	Size: 40 m	Size: 60 m	Size: 80 m
$10^{16.5}$	0.14°	0.10°	0.09°	0.07°
10^{17}	0.151°	0.101°	0.088°	0.059°
10^{18}	0.141°	0.097°	0.089°	0.079°
10^{19}	0.140°	0.099°	0.099°	0.079°

Table 2: The angular resolution for azimuth angle with the filter as nchan ≥ 4 is given for different energies and different station baselines.

4. Summary

A study was performed to determine the relative performance of an ARA detector station for different geometrical dimensions. We find that the effective area at reconstruction level increases for larger baselines. At the same time the angular resolution increases. The fact that the time window needs to be increased at trigger level has been taken into account by adjusting the thresholds. These findings will be used to inform the decision for future station size including in the deployments planned for the austral season 2017/18.

Baseline Size	Passing Rate (nchan $\geq$ 4)	Angular Resolution
20 m	8.14 x 10^{-4}	0.141°
40 m	1.08 x 10^{-3}	0.097°
60 m	1.28 x 10^{-3}	0.089°

Table 3: A table summarizing the variation of passing rate and angular resolution for different baseline sizes at $E = 10^{18}$ eV.

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