PROCEEDINGS OF SCIENCE

The Askaryan Radio Array: latest results and ongoing work

Simona Toscano[a,*] **on behalf of the ARA Collaboration**

[a] *Université Libre de Bruxelles, Science Faculty CP230, B-1050 Brussels, Belgium.*

E-mail: toscano@icecube.wisc.edu

The Askaryan Radio Array (ARA) is searching for high-energy neutrinos (>10 PeV) from the cosmos using clusters of antennas buried under the South Pole ice sheet at a maximum depth of 200 m. ARA is looking at the radio Cherenkov emission generated when neutrinos interact with the surrounding medium. The array consists of 5 radio stations, each of them monitoring an independent portion of the ice to maximize the detector effective volume. ARA stations use a combination of vertically polarized (VPol) and horizontally polarized (HPol) antennas, as well as in-ice calibration devices (calpulser) for antenna positioning and ice properties studies. One of the newest ARA stations has been equipped with an independent phased array detector allowing to lower the trigger threshold and consequently improve the array sensitivity at low energies. ARA has been taking data since 2012 and analysis of the full data set is ongoing. In this contribution we present the latest results in the ARA search for cosmic neutrinos, which produced the best limit from an in-ice radio detector above 100 PeV. Additionally we discuss calibration efforts and ongoing work in analysis and reconstruction.

9th International Workshop on Acoustic and Radio EeV Neutrino Detection Activities - ARENA2022
7-10 June 2022
Santiago de Compostela, Spain

*Speaker

PoS(ARENA2022)001

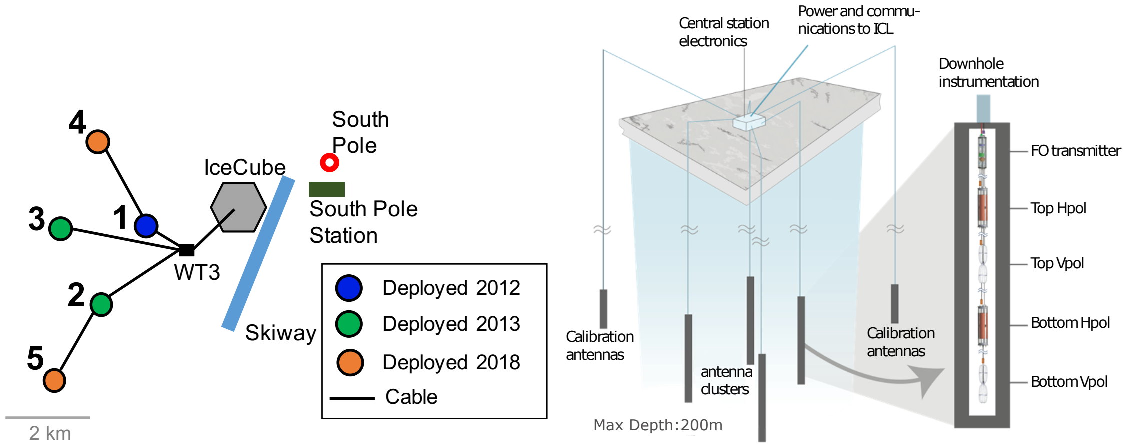

Figure 1: *Left*: Layout of the ARA5 array, showing the positions and the year of deployment for each station as well as local landmarks. Stations are cabled to the IceCube Counting Laboratory (ICL) for power and network. *Right*: Schematic of an ARA station, showing the layout of the downhole instrumentation.

1. Introduction

Cosmic accelerators are known to produce particles with energies exceeding 10^{20} eV, but the acceleration and propagation processes are still not understood. Cosmic neutrinos are produced in interactions of these high-energy hadronic particles with photons and matter surrounding the source or during propagation. Neutrinos, being weakly interacting particles, have the potential to escape unscathed from the inner part of the accelerators where cosmic rays have been generated, providing an unobstructed and intact view of the sources. However, at the highest energies (> 10 PeV), the expected flux of cosmic neutrinos is low and Gigaton optical Cherenkov detectors, such as IceCube [1], although successful, accumulate only limited statistics due to their relatively small instrumented volume. To overcome this challenge, several neutrino detectors [2–4], are currently exploiting the high transparency of the Antarctic ice at radio frequencies, where UHE neutrino signatures are visible over distances of the order of 1 km. Neutrino interactions in dense media produce a sub-ns radio pulse due to the Askaryan effect [5, 6]. The use of the radio technique allows to instrument large volumes of ice with sparse instrumentation, making affordable to build Teraton-scale arrays at relatively low-cost.

2. The Askaryan Radio Array

The Askaryan Radio Array (ARA) is a radio neutrino detector located a few kilometers grid-west of the geographic South Pole in Antarctica, next to the IceCube experiment [7]. The ARA detector consists of 5 independent stations, each equipped with a total of 16 antennas detecting vertically- and horizontally- polarized radiation, VPol and HPol respectively. Antennas are sensitive to radiation in the 150-850 MHz band and they are deployed at the bottom of 200 m depth holes in four strings. Two calibration strings deployed about 40 m away from the center of the station are used to perform *in-situ* calibration of the station geometry and timing. Each calibration string includes a VPol as well as a HPol antenna capable of emitting broad-band RF pulses detectable by the 16 antennas of the ARA station. The 2-km spacing between stations allows to monitor independent volumes of ice, maximizing the instrument aperture. The newest ARA Station 5 (A5) has been equipped with an additional central antenna string with its own triggering instrument called the Phased Array (PA). The PA is a digital interferometer with the ability to increase the trigger efficiency at a low Signal-to-Noise Ratio (SNR) using a beamforming triggering. Although deployed together, A5 and PA are two independent detectors. Recently, the ARA collaboration has published an analysis using a data set of 6 months of PA-only data [8]. The PA system and the latest result on the UHE neutrino flux with the PA instrument are discussed in [9]. The ARA detector has been taking data since 2012 although its configuration has been changing over time, increasing the array size. The ARA array layout is shown in Figure 1 together with the deployment timeline and the downhole instrumentation.

2.1 Calibration efforts

To search for UHE neutrinos raw data need to go through a calibration procedure which was initially designed for A2 and A3 and later on applied to A4 and A5[1]. A relative timing calibration between antennas of $O(ns)$, and a geometrical location accuracy of $O(10cm)$ are required to achieve a precise vertex reconstruction, which is essential for neutrino identification and astrophysical searches. Moreover, ice properties need to be studied in detail to allow for a correct treatment and interpretation of the radio signal propagation and vertex reconstruction.

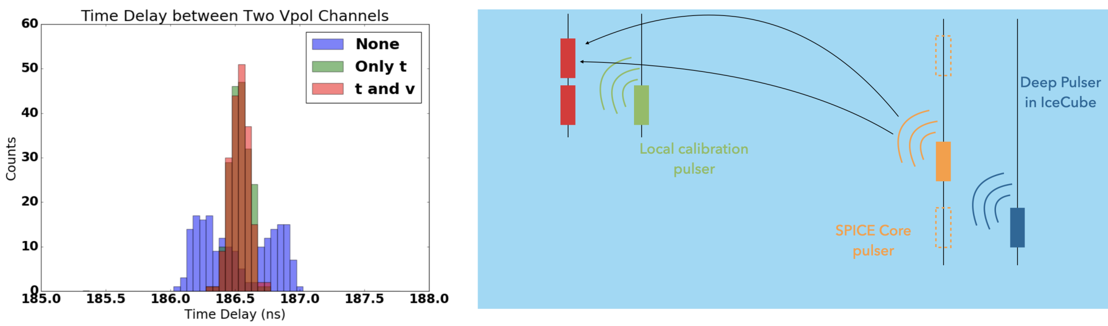

Figure 2: *Left*: Time delay between two VPol channels in A5. The three histograms show the improvement from non-calibrated (blue), only-time calibrated (green) and fully-calibrated (red) waveforms. *Right*: Schematics of the geometry calibration procedure, where several local and far pulsing sources are used in a minimization procedure to find the antenna positions.

Timing and antenna positioning Signals received at the antennas are processed and sent to the surface through fibers [2]. Once the signal arrives at the surface it is stored in the circular buffer of a custom integrated circuit, the IceRaySampler 2 (IRS2) chip, with a sampling speed tuned to 3.2 GS/s, allowing for a buffering capability of up to 10 μs. In the IRS2 chip data are sampled through a Switched Capacitor Array (SCA). The SCA consists of 128 sampling capacitors per channel, equally divided into even and odd samples on two delay lines and each with a delay element requiring individual calibration in timing. In addition to that, the ADC-to-voltage conversion gain needs to be determined for each of the 32768 buffer elements on each channel to obtain a proper

[1]Calibration of A1 is currently ongoing

voltage calibration. Calibration of the digitizer is performed using pre-deployment sine waveforms, fed directly into the system. The calibration procedure has been described in detail in [7, 10]. Figure 2 (left) shows the time difference distribution of calibration pulse signals arriving in two VPol channels of A5, before (blue histogram) and after (green and red) the calibration process. As can be seen, the obtained time resolution (width of the red histogram) is of the $O(100ps)$ for this specific channel pair. Similar results are found for all channels of all calibrated stations.
As already mentioned, antenna positions must be known to within a few cm so that the signals coherently sum across the entire frequency band. This means that positions, usually surveyed to the meter, must be corrected using several local (calpulser) and global (SPICE core and IceCube Deep pulsers) calibration sources as shown in Figure 2 (Right). Signals from several sources are observed at different times in different antennas, depending mainly on the incoming direction. Hence, information on antenna positions and ice properties can be extracted looking at the time delays between pairs of channels receiving the signal and comparing to expectations from ray-tracing algorithms. Our process of finding the antenna positions in ice involves simultaneously fitting the cable delays, antenna positions, and the local ice model, each carrying their own approximate uncertainties.

Ice properties measurement at the South Pole Since the installation of the first stations, the ARA collaboration has been performing extensive radio glaciology campaigns to better characterize the ice properties at radio frequencies at the South Pole [11]. Several sources were used to broadcast

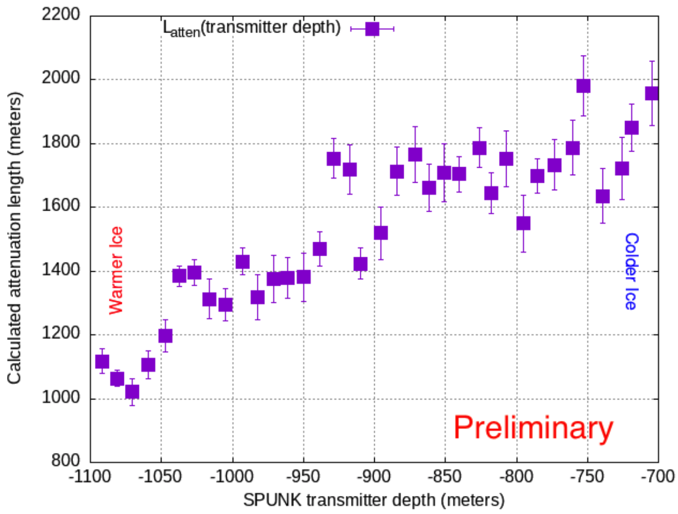

Figure 3: Measurement of the ice radio-frequency attenuation length at the South Pole as function of the transmitter (SPUNK) depth.

over horizontal baselines of 1–5 km. Two transmitters are deployed to depths of up to 1500 meters and frozen into boreholes drilled for the IceCube detector (IC1S, IC22S). Another source is a retrievable pulse generator that was mounted on a winch and lowered into a 1700m borehole created by the South Pole Ice Core Experiment (SPICE). Signals from the transmitters were recorded on the antennas of the five ARA stations. Figure 3 shows the measurement of the radio frequency attenuation length as a function of depth. Broadcasting over long horizontal baselines permit to estimate the radio-frequency attenuation in the upper (colder) half of the Antarctic ice sheet, target of the majority of neutrino interactions seen by ARA. A measurement of the birefringence[2] was performed using the same data. Since birefringence is related to the crystal orientation, the relative position of ARA receivers with respect to transmitters and the local ice flow direction need to be taken into account. The left plot of Figure 4 shows the geometry of ARA receiver stations relative to transmitter sources in IceCube and the SPICE borehole.

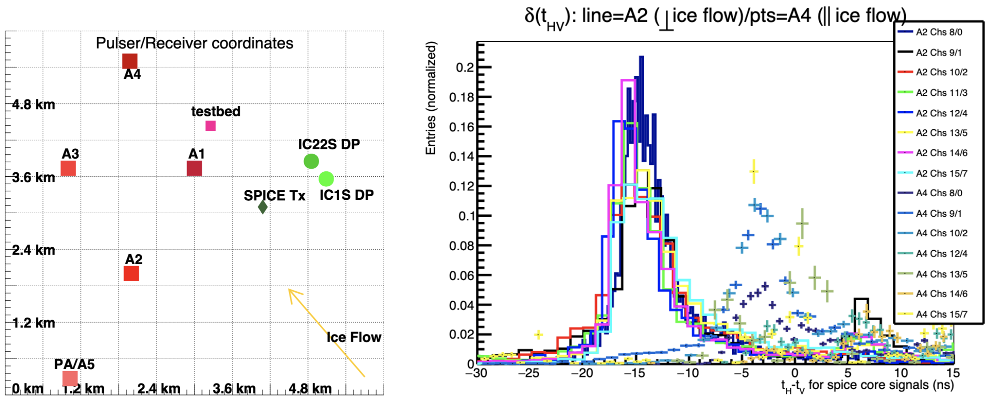

Figure 4: *Left*: Geometry of ARA receiver stations (red/pink) relative to transmitter sources in IceCube (IC1S, IC22S) and SPICE borehole. The local ice flow direction is also shown. *Right*: Summary of birefringence measurements (transmitter=Spice Core pulser), comparing data from stations parallel vs. perpendicular to ice flow. For more details we refer to [11].

The right plot shows the time difference in HPol and VPol receiving antennas between stations parallel and perpendicular to the ice flow for signal transmitted from the SPICE Core pulser. Asymmetries in the propagation of the horizontal versus vertical polarizations was measured to the level of 0.15%. Details about the experiment setup and analysis can be found in [11].

3. Latest results on diffuse neutrino search

Being the first stations to be calibrated ARA Station 2 and 3 (A2, A3) have been used to search for a diffuse flux of UHE neutrinos. Both stations have been collecting data since Feb 2013. The latest ARA diffuse analysis [12] uses data from 2013 to 2016, corresponding to 8 station-years. The diffuse search analysis was performed in a blind fashion to avoid bias, with event selection criteria tuned on only 10% of the full data set, randomly sampled over the entire lifetime. Two independent analyses were developed for this search leading to similar results. The separation between signal and noise was achieved with a bivariate cut in the plane of peak cross correlation C_{sky} (reconstruction quality parameter) versus root power ratio (signal strength). Both analyses find 0 events on an expected background of 10^{-2}. The 90% confidence-level upper limit on the all-flavor diffuse neutrino flux is the best limit from an in-ice radio detector above 100 PeV and is shown as a black line in Figure 5. This ARA result is compared with existing limits from other experiments and cosmogenic flux expectations. An analysis to search for a UHE diffuse neutrino

[2]The polarization dependence of radio-frequency signal amplitude propagating through the cold polar ice

flux in the full data set is currently under way. The projected trigger-level single event sensitivity (TL SES) for the full ARA data set, reaching on disk almost 25 station-years, place ARA as the world's leading experiment in the 1-100 EeV energy range.

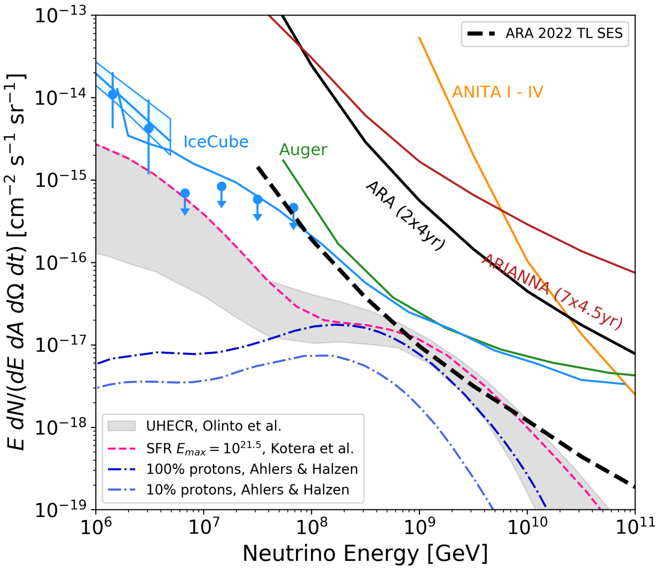

Figure 5: The 90% confidence-level upper limit on the all-flavor diffuse flux of neutrinos set by the latest ARA analysis using 8 station-years [12]. We also plot the projected trigger-level single-event sensitivity (TL SES) for the five-station ARA array by 2022 as a black- dashed curve. This accounts for the full data set currently on disk as well as the lower trigger threshold of the PA.

4. Reconstruction of neutrino properties

The discovery and study of UHE neutrinos entail reconstruction capabilities of neutrino properties such as the energy and the arrival direction. Reconstructing the neutrino requires reconstructing properties of the incident electric field, which depends on the signal direction, strength and polarization, distance of the interaction vertex and the viewing angle, i.e. the angle between the neutrino direction and the launch vector (the initial direction of signal propagation). A paper describing the methodology used in ARA and reconstruction performance is in preparation within the collaboration.

Vertex reconstruction The interaction vertex position (θ, ϕ, R) is reconstructed using interferometry. In this process, pulse arrival times from data are compared with simulation and the difference is minimized to find the correct solution. Because of the changes in the index of refraction ray paths will bend in ice. Hence, the simulated pulse arrival time is calculated using an analytic ray-tracing algorithm for a given ice model. Figure 6 shows the difference between the reconstructed vertex position and the true value for a set of neutrino vertices generated at 1 EeV at random positions around the ARA detector. The standard deviations of the distributions, corresponding to their FWHMs (Full Width Half Maximum), are 3°, 1.8° and 100% (meaning that 50% of events are reconstructed within a factor of 2) for zenith and azimuth angles and distance respectively.

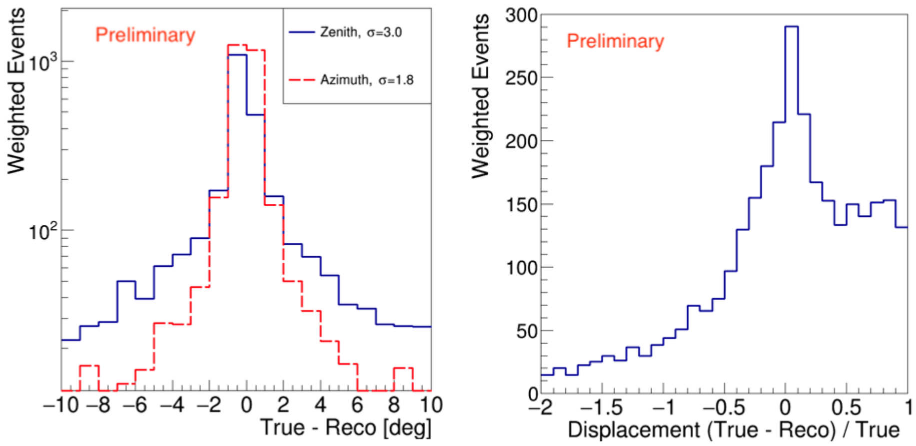

Figure 6: *Left*: Performance of the interferometric reconstruction for the zenith and azimuth angles. *Right*: Performance of the interferometric reconstruction for the vertex distance.

Shower energy reconstruction The neutrino shower energy is reconstructed using a least-squares minimization. We explore the three-dimensional parameter space of shower energy (E_{sh}) and neu-

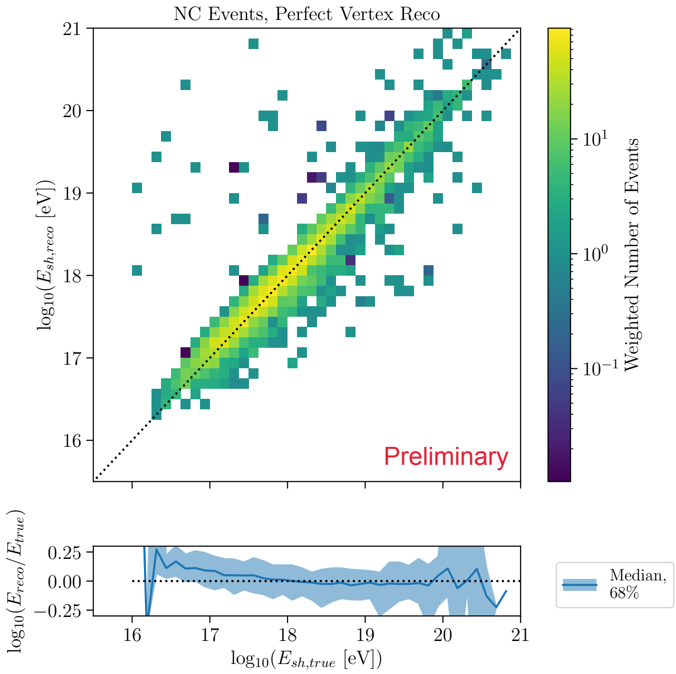

Figure 7: Performance of the energy reconstruction algorithm for a sample of simulated hadronic neutrino interactions generated with an E^{-2} spectrum. The vertex is assumed to be known.

trino direction (θ_ν, ϕ_ν) and find the values that agree the most with observations. For each hypothesis ($E_{sh}, \theta_\nu, \phi_\nu$) the signal is propagated and folded with the system response before comparison with the observed values. This technique is called forward-folding [13] and used to reconstruct neutrino properties in other radio neutrino experiments. Figure 7 shows the correlation between the reconstructed shower energy and the true value for a set of hadronic showers (only neutral current events) of known vertex position. The bottom panel shows the error (median and 68% containment regions) as a function of energy. In a broad energy range no bias is observed.

5. Conclusions

The Askaryan Radio Array has been taking data since 2012. Calibration efforts have delivered the most sensitive data set in the 1–100 EeV energy range. The latest diffuse search for UHE neutrinos only uses one third of the data on disk. With an accumulated data of ~25 station-years ARA has the power to start constraining cosmogenic models and a real chance of making a discovery in the very near future.

References

[1] M. G. Aartsen et al. The IceCube Neutrino Observatory: Instrumentation and Online Systems. *JINST*, 12(03):P03012, 2017.

[2] P. Allison et al. Design and Initial Performance of the Askaryan Radio Array Prototype EeV Neutrino Detector at the South Pole. *Astropart. Phys.*, 35:457–477, 2012.

[3] J. A. Aguilar et al. Design and Sensitivity of the Radio Neutrino Observatory in Greenland (RNO-G). *JINST*, 16(03):P03025, 2021.

[4] S. W. Barwick et al. Radio detection of air showers with the ARIANNA experiment on the Ross Ice Shelf. *Astropart. Phys.*, 90:50–68, 2017.

[5] G. A. Askar'yan. Excess negative charge of an electron-photon shower and its coherent radio emission. *Zh. Eksp. Teor. Fiz.*, 41:616–618, 1961.

[6] G. A. Askar'yan. Coherent Radio Emission from Cosmic Showers in Air and in Dense Media. *Soviet Journal of Experimental and Theoretical Physics*, 21:658, September 1965.

[7] P. Allison et al. Performance of two Askaryan Radio Array stations and first results in the search for ultrahigh energy neutrinos. *Phys. Rev. D*, 93(8):082003, 2016.

[8] P. Allison et al. Low-threshold ultrahigh-energy neutrino search with the Askaryan Radio Array. *Phys. Rev. D*, 105(12):122006, 2022.

[9] K. Hughes and the ARA Collaboration. Results from a low-threshold ultrahigh-energy neutrino search with the Askaryan Radio Array. In *These proceedings*, 2022.

[10] Paramita Dasgupta, Kaeli Hughes, et al. The Calibration of the Geometry and Antenna Delay in Askaryan Radio Array Station 4 and 5. *PoS*, ICRC2021:1086, 2021.

[11] P. Allison et al. Long-baseline horizontal radio-frequency transmission through polar ice. *Journal of Cosmology and Astroparticle Physics*, 2020(12):009, dec 2020.

[12] P. Allison et al. Constraints on the diffuse flux of ultrahigh energy neutrinos from four years of Askaryan Radio Array data in two stations. *Phys. Rev. D*, 102(4):043021, 2020.

[13] Christian Glaser, Anna Nelles, Ilse Plaisier, Christoph Welling, Steven W. Barwick, Daniel García-Fernández, Geoffrey Gaswint, Robert Lahmann, and Christopher Persichilli. NuRadioReco: A reconstruction framework for radio neutrino detectors. *Eur. Phys. J. C*, 79(6):464, 2019.