Abstract. As of this writing, there are three dedicated experiments, all based in Antarctica, which seek first-ever measurement of the ultra-high energy neutrino flux at Earth. All three (ANITA, ARA and ARIANNA) exploit the Askaryan Effect to detect the so-called cosmogenic neutrinos which should result from interactions of ultra-high energy baryons with the Cosmic Microwave Background Radiation (CMBR). Photoproduction of those neutrinos, via $N\gamma \rightarrow \Delta \rightarrow N\pi^\pm$, with subsequent weak decays of those pions resulting in neutrinos. Ice weak and neutral scattering of those neutrinos off ice molecules can yield in a detectable pulse of coherent, radio-frequency radiation. We summarize the three experiments, and discuss prospects.

History
Radio Detection of UHE Neutrinos, Theory
Coherent radio Cherenkov studies go back to Jelly, who first studied radio signals from cosmic ray air showers[1, 2]. Askaryan[3] subsequently predicted a net charge imbalance in dense media and coherent radio power scaling like the energy of the shower squared, providing impetus for continued progress in UHE air shower studies. The basic idea of coherent detection of radio-frequency Čerenkov radiation emanating from a neutrino induced electromagnetic shower is straightforward. The number of particles $N$ in a shower of energy $E$ is proportional to $E$. The shower has an approximately fixed ratio of electrons to positrons ($\simeq 1.25$) arising primarily because of scattering of atomic electrons into the developing shower; the shower will thereby build up an effective negative electrical charge proportional to its energy. Čerenkov radiation, which is intrinsically broadband, will be produced by this relativistically moving charge. If the electromagnetic shower develops in a dense, but transparent medium, the energy in the shower will be concentrated on a Čerenkov front which can travel a long distance with little attenuation. The radiation will be emitted incoherently for very small wavelengths relative to the lateral size of the shower, but coherently for wavelengths greater than the lateral size of the shower ($\sim 10$ cm in ice). At such radio-frequencies, the power emission will be proportional to the shower energy squared. This rapid increase in power with energy substantially compensates for the decreasing neutrino flux, which has an integral spectrum falling roughly as $1/E^2$. A test beam experiment at SLAC by Gorham and Saltzberg has given the most direct confirmation of the Askaryan effect[10].

Russian collaborators performed the first experimental studies, and laid the initial groundwork for development of a radiowave-based neutrino detection experiment. That previous work includes the definitive measurements at Vostok of the temperature profile of the ice down to 2 km (1.5 km above bedrock), as well as measurement of the frequency and temperature

Status of RadioWave Neutrino Detection

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dependence of the ice absorption of radio waves. A pilot experiment (“RAMAND”, for Radio wave Antarctic Muon And Neutrino Detector) tested many aspects of the neutrino radio detection idea at Vostok between 1985-1990, including critical initial measurements in Antarctica of natural and man-made radio impulse backgrounds[4, 5, 7, 8, 9]. Unfortunately, that nascent effort was abruptly terminated in 1991, when the Soviet political (as well as scientific) infrastructure collapsed.

In 1994, George Smoot and collaborators at the Lawrence Berkeley Lab characterized the radio-frequency environment at South Pole (“RAND”), however, that project also lacked follow-up. The RICE experiment, which first deployed in-ice antennas in 1995, represented a prototype of the in-ice neutrino detection technique and can perhaps be credited with first demonstrating the operational feasibility of such an effort.

Simulations of the signal-generation mechanism are, in principle, straightforward. For definiteness, consider a $\nu_e$ undergoing a charged current interaction, $\nu_e + N \rightarrow e + N'$. The primary UHE neutrino transfers most of its energy to the electron, which quickly builds an exponentially increasing shower of $e^+e^-$ pairs. The number of pairs $N_e$ scales like the primary energy. In the most populated region of the shower, at the “bottom” of its energy range, a charge imbalance develops as positrons drop out and atomic electrons scatter in. Detailed Monte Carlo calculations by Zas, Halzen and Stanev (ZHS)[11] and confirmed by later GEANT simulations find that the net charge of the shower is about 20% of $N_e$. The electric field produced by this relativistic pancake is dominated by coherent Cherenkov radiation for wavelengths in the radio frequency region. Equivalently, for wavelengths large comparable to the transverse size of the shower ($\sim 2r_{Moliere}$, or $\sim 10$cm in ice), the relativistic pancake can be treated as a single, extended, radiating charge. (Clearly, in the limit $\lambda \rightarrow \infty$, the radiating region approaches a point charge.)

Cold polar ice offers several advantages which make it an extremely attractive candidate target medium for neutrino detection. In addition to comprising a huge, uniform target, measurements to date indicate that cold ice ($\leq -50^\circ$C) has extremely long field attenuation lengths, of order $\geq 1-3$ km for 100 MHz - 1 GHz radio signals[12], whereas optical photons in ice have absorption and scattering lengths which are typically an order of magnitude smaller.

Ultra-high energy (UHE) neutrinos point back to sources of high energy cosmic rays, providing an identification of the source as well as a powerful test of models for the acceleration mechanism. Detection of UHE neutrino fluxes simultaneous with gamma-ray bursts would provide essential information on the nature of these extraordinarily luminous sources[13]. At even higher energies, “GZK” neutrinos may help identify more exotic sources such as topological defects[14]. In the realm of particle physics, detection of UHE neutrinos from cosmological distances, if accompanied by flavor identification, may permit measurement of neutrino oscillation parameters over an unprecedented range of $\Delta m^2[15, 16]$, or detect $\nu_\tau$ via “double-bang” signatures[17]. The angular distribution of upward-coming neutrino events could be used to measure weak cross-sections at energies unreachable by man-made accelerators[18]. Alternately, if the high energy weak cross-sections are known, they can be used to test Earth composition models along an arbitrary cross-section (so-called ‘neutrino tomography’)[19]. Most exciting of all, as the history of astronomy has demonstrated, the implementation of each new technology has been rewarded with spectacular, yet unanticipated, discoveries.

Radio Detection of Neutrinos, Experiment
The ANITA Experiment
Initiated in 2003, the Antarctic Impulsive Transient Antenna (ANITA) is a balloon-borne antenna array primarily designed to detect radio wave pulses caused by neutrino collisions with matter, specifically ice. The basic instrument consists of a suite of 40 quad-ridged horn antennas, optimized over the frequency range 200-1200 MHz, with separate outputs for vertically
vs. horizontally incident radio frequency signals, mounted to a high-altitude balloon. From an elevation of $\sim 38$ km, the balloon scans the Antarctic continent in a circumpolar trajectory. Details on the ANITA hardware, as well as the triggering scheme crucial to the analysis described herein, are provided elsewhere[20].

Two one-month long missions (ANITA-I: Dec. 2006-Jan. 2007 and ANITA-II: Dec. 2008-Jan. 2009) have yielded world’s best limits to UHE neutrino flux in the energy range to which ANITA is sensitive[21, 22]. A recent analysis of the ANITA-I data sample has also provided a statistically large (16 events) sample of radio frequency signals attributed to geosynchrotron radiation associated with cosmic-ray induced extensive air showers (EAS)[23]. That analysis not only demonstrated that radio wave detectors can independently trigger on EAS, but also established the air-borne strategy as an efficient EAS detection technique, and further affirmed the broad range of science accessible to ANITA.

The hierarchial ANITA-II trigger allows a relatively low neutrino detection trigger threshold, while maintaining a tolerable ($\sim$Hz) thermal noise data rate written to disk. In contrast to ANITA-I, only signals from the VPol channel of the dual-polarization horn antennas contribute to the ANITA-II trigger. Following the antenna, signals routed through the ‘trigger’ (vs. ‘digitization’) path are tested for their spectral power in four frequency bands, approximately covering the intervals (in MHz) 200 → 350, 330 → 600, 630 → 1100 and 150 → 1240, respectively. This partitioning is performed in order to provide rejection power against narrow-bandwidth anthropogenic backgrounds, while retaining high efficiency for sharp duration (temporally), large-bandwidth neutrino signals. The frequency-banded signals are then passed through a tunnel-diode, which integrates roughly 7-ns units of data and provides a unipolar (negative) output pulse. The lowest-level trigger requires signal in one of the four frequency bands at a level exceeding approximately $2.3\sigma_V$, with $\sigma_V$ the rms of the typical tunnel-diode output voltage at this point.

The hierarchial trigger and small occupancy allows ANITA to collect data very close to the intrinsic thermal noise floor, resulting in excellent sensitivity. Although no neutrinos have been found thus far, ANITA has, as mentioned previously, nevertheless demonstrated the ability to self-trigger on radio emissions from air showers and is, to date, the only existing experiment to have successfully done so. That observation is an important consideration in trigger and hardware modifications planned for ANITA-3, which is slated to fly in Dec., 2013.

The ARA Experiment

ARA stations are designed to detect a highly linearly-polarized RF impulse arriving from any direction, either as an approximate plane wave (for distant sources) or a spherical wave for closer sources. The individual antennas that comprise a station must have response that is preferably dipole-like in angular extent, but the antenna array must also be sensitive in two orthogonal polarizations to avoid any bias against detecting arbitrary planes of polarization, since the RF impulses that arise from the Askaryan effect may be observed at an arbitrary angle with respect to the plane of polarization. Because of practical limitations on drilling, antennas should fit within a 15 cm diameter borehole, and also be below the $\sim 150$ m thick firn, the top layer of the ice sheet made of compacted snow of density lower than that of solid ice. Due to the refractive index gradient, signals within the firn are subject to ray-bending which complicates triggering and reconstruction, and also leads to an effective inverted horizon, cutting off the detectability of more distance sources in the ice. Since South Polar ice has its highest RF clarity in the coldest ice, the antenna array response should be optimized for detection in the upper 1 to 1.5 km of ice, although deeper events will also be seen.

The prototype ‘testbed’ station deployed in 2010-11 at 20–30 m ice depths[24], with electronics and antennas very similar to the full-fledged ARA01 (2011-12) and ARA02/ARA03 (2012-13) stations to be deployed to 200 m depth. The ARA testbed installation was completed in the third
week of January 2011, at a location approximately 1.8 km grid East of the IceCube detector, and has been operating nearly continuously since then.

The projected science performance of ARA-37 is summarized in Figure 1.

The ARIANNA Experiment

In the TeV-PeV energy range, Antares/Baikal and IceCube represent two complementary approaches to neutrino detection, namely in-water vs. in-ice. Carrying the analogy further, the difference between ARIANNA and ARA can be likened to the distinction between Antares and the Lake Baikal experiments, which are themselves based in salt vs. fresh water. Whereas ARA is sited at South Pole, and draws power off the South Polar grid, ARIANNA is sited at Minnabluff, just below the snow surface, on the Ross Ice Shelf, in a region shielded by local mountains from the radio background presented by McMurdo Station. As a result, the ARIANNA hardware design targets minimal power consumption, but requires none of the narrow-band notch filtering required by ARA.

Relative to ANITA, ARA and ARIANNA obtain a lower experimental energy threshold by locating their antennas ‘close’ to a prospective neutrino interaction point. The two experiments are compared, in tabular form, in Table 2.
Conclusions and Prospects

Prospects for detection of ultra-high energy neutrinos have recently brightened with the announced observation of two ultra-high energy neutrino candidates by the IceCube experiment. Although their origin has yet to be established, this observation nevertheless may, at long last, usher in the era of the ‘neutrino telescope’. Correspondingly, the ARA and ARIANNA projects are now in the prototyping phase, in order to establish the hardware and deployment procedures that are anticipated for ultimate arrays 100-1000x larger than their current scales.

The ANITA experiment, although forced to an experimental threshold 1-2 orders of magnitude above the expected peak of the cosmogenic neutrino energy spectrum and therefore perhaps less likely (given our current understanding) to establish the UHE neutrino flux than the in-ice projects, nevertheless has the distinction of being, thus far, the only experiment to self-trigger on the radiowave signal resulting from a developing, in-air cosmic ray shower. The trigger and electronics for the ANITA-3 mission, scheduled for 2013-14 will enhance the direct CR detection rate, relative to ANITA-2, by at least two orders of magnitude, and, by the conclusion of it’s flight, will have an ultra-high energy cosmic ray sample numerically competitive with Auger, albeit with somewhat degraded resolution.

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