Acoustic Neutrino Detection in Ice: Past, Present, and Future

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Abstract. Acoustic neutrino detection is a promising technique to instrument the large volumes required to measure the small expected flux of ultra-high energy cosmogenic neutrinos. Using ice as detection medium allows for coincident detection of neutrino interactions with acoustic sensors, radio antennas and optical light sensors with the benefit of cross calibration possibilities or independent measurements of the the same event. We review the past development of the field and discuss its current status and challenges. Results from site exploration studies, mainly by the South Pole Acoustic Test Setup (SPATS) which has been codeployed with the IceCube neutrino telescope at South Pole, and current physics results are presented. Current ideas for the design, calibration, and deployment of acoustic sensors for new projects are shown. The possible role of the acoustic technique in future in-ice neutrino detectors is discussed.

Keywords: ultra-high energy neutrinos, acoustic detection, Antarctica, SPATS
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INTRODUCTION

In the year 2012 we celebrate the 100$^{\text{th}}$ anniversary of the discovery of cosmic rays. But even after a hundred years of research many questions about the origin, acceleration, and composition of ultra-high energy cosmic rays remain unanswered. The multi-messenger approach, combining the information gained from electromagnetic radiation from radio to TeV photons, charged cosmic rays, and neutrinos promises to resolve these problems. Neutrinos are ideal messengers in the sense that they are undeflected by magnetic fields during their propagation and that they rarely interact, preserving their initial direction and energy until detected at Earth.

Ultra-high energy (UHE; $E_\nu \gtrsim 100$ PeV) neutrinos, offer a very rich physics program, including astrophysics, cosmology, particle physics, and physics beyond the Standard Model:

- Cosmogenic neutrinos are produced in the interactions of charged cosmic rays at ultra-high energies with the cosmic microwave background [1], typically within a distance of a few ten Mpc of the source [2]. Thus, for very far sources, they allow for a good pointing towards the source. The flux of UHE cosmogenic neutrinos is very sensitive to the chemical composition of the charged cosmic rays (e.g. [3, 4]).
- Since UHE neutrinos reach us from very high redshifts, their flux is also sensitive to the evolution of cosmic ray sources in the earlier universe (e.g. [3]). Resonant Z boson production could reveal the cosmic neutrino background and allow us to determine the neutrino masses [5].
- Measuring the neutrino flux with different mass overburden, e.g. at different zenith angles with an underground detector, will allow us to determine the neutrino absorption in the Earth and thus probe the neutrino nucleon cross section at high center-of-mass energies [6].
- There are many theoretical models of physics beyond the Standard Model which predict large deviations of the neutrino nucleon cross section from the Standard Model at high energies (e.g. [7, 8]). UHE neutrinos will allow us to test many of these models.

To achieve all these goals we need to measure UHE neutrinos with reasonable statistics and good energy and direction resolution. This requires a detector with a volume ≥ 100 km^3. There are different experimental techniques to build such large scale detectors which are currently pursued either in running experiments or as feasibility studies.

Radio detection experiments are looking for short radio pulses in the hundreds of MHz to GHz frequency range emitted by the electromagnetic cascade generated in a neutrino interaction. These experiments can be embedded in radio-transparent, homogeneous media like ice [9] or salt, or use balloons or satellites to observe large natural ice volumes. Also, observations of the Moon with radio telescopes are employed to look for neutrino interactions in the lunar regolith [10].

Extensive air shower experiments can detect UHE neutrinos either as highly inclined, "young" air showers, where the primary neutrino has penetrated deep into the atmosphere before interacting, or as up-going air showers from Earth-skimming neutrinos. The HiRes detector [11] and the Pierre Auger Observatory [12] have used these methods to set upper limits on the flux of UHE neutrinos.

Finally, acoustic neutrino detectors are searching for ultrasonic pressure pulses generated in the instantaneous heating and expansion of the medium induced by electromagnetic and hadronic cascades. Water [13], ice, salt, and permafrost soil [14] have been discussed as detection media. In this work we review the development, status and perspectives of acoustic neutrino detection in ice.

A BRIEF HISTORY OF ACOUSTIC NEUTRINO DETECTION IN ICE

Acoustic neutrino detection in liquids is based on the thermo-acoustic model [15, 16]: When a neutrino of any flavor interacts via a charged- or neutral current interaction, a hadronic and/or electromagnetic cascade develops at the interaction vertex, which carries a significant amount of the neutrino energy. In a dense medium this energy is dissipated in a volume of typically 10 m in length and a few centimeters in diameter. This leads to an instantaneous heating of the cascade volume. The corresponding rapid expansion of the volume propagates as an ultrasonic shock wave perpendicular to the cascade axis and can be measured as a short (i.e. with a broad frequency spectrum), bipolar pressure pulse with a duration of several ten microseconds. The details of the pulse depend on the material properties of the medium and on the modeling of the cascade energy deposition density.

The first ideas about acoustic detection of particles in liquids date back to the 1950s [17]. It was then revived in the 1970s and studied in great detail in the context of the DUMAND project, leading to detailed calculations of the expected acoustic signals from the thermo-acoustic model [18, 19] and first measurements with a proton beam from an accelerator dumped in water [20].

With the design and construction of the AMANDA optical Cherenkov neutrino telescope at South Pole interest in acoustic neutrino detection in ice began. Ice, in contrast to water, allows for the propagation of longitudinal (pressure, p) sound waves and transverse (shear, s) waves. The formalism of the thermo-acoustic model can be expanded to the case of solid media and predicts the excitation of mainly pressure waves by neutrino interactions (cf. e.g. [21]); shear waves can be generated at impurities in the crystal structure of the medium.

Acoustic signals predicted by the thermo-acoustic model scale, for equal energy deposition densities, with the thermo-elastic properties of the detection medium. Due to the nearly equal matter densities of water and ice the energy deposition density from a neutrino interaction is very similar. From detailed calculations, taking into account the elastic properties of ice, the amplitudes of neutrino-induced thermo-acoustic signals in ice are expected to have amplitudes which are larger by a factor of about four compared to water [21]. This is supported by measurements in the Aachen Acoustic Laboratory [23] where laser-induced acoustic pulses in water and ice have been studied [22]. Figure 1 shows that the scaling of the signal amplitude from water to ice is compatible with expectations. It can also be seen that in ice, due to the larger speed of sound, higher frequency signals are generated.

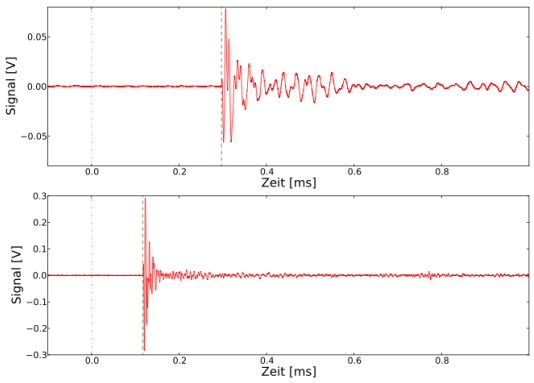


FIGURE 1. Laser-induced acoustic pulses in water (top) and ice (bottom) generated with identical laser pulses (from [22]).

Phenomenological studies of the ice acoustic properties predicted an acoustic attenuation length of several kilometers [24, 25] and low background noise [25], which would allow for very large, sparsely instrumented detection volumes. Subsequent studies favored the radio technique as being more sensitive than acoustics [26]. In the same article (Ref. [26]) the possibility of hybrid detection, using several complementary techniques (radio and optical) is discussed. In the following years experimental limits on the flux of high energy neutrinos became more stringent and theoretical flux predictions decreased accordingly. It became clear that detector volumes ≥ 100 km^3 are required which are difficult to achieve with optical Cherenkov detectors. Since radio and acoustic signals were expected to have similar attenuation lengths, hybrid radio-acoustic detectors were discussed and simulation studies showed very promising results [27].

However, it was clear that the predicted acoustic properties of the ice need to be tested by in-situ measurements. Different piezoelectric sensors for use in ice were developed and characterized [28] and sound generation in ice by an accelerator proton beam was studied [29]. These efforts led to the construction and deployment of the South Pole Acoustic Test Setup (SPATS) that will be discussed later in this work.

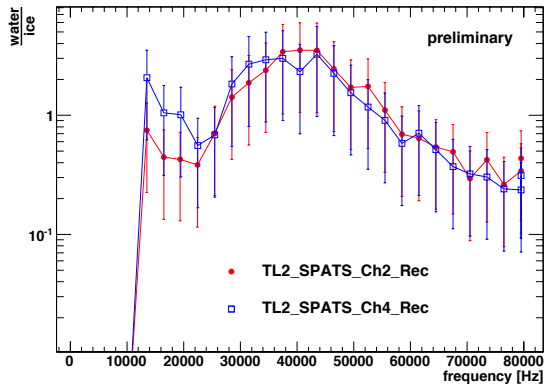


FIGURE 2. Ratio of the sensitivities measured in water and ice of two SPATS sensor channels (from [33]).

MEASURING ACOUSTIC WAVES IN ICE

Building a large acoustic detector with reasonable energy and direction resolution requires to fully understand the sensor response in-situ. Sensor sensitivity is not just a single number to convert incident pressure to output voltage measured at the sensor, but is a function of incident wave direction, wave mode, temperature, and possibly other environmental parameters. Since no pre-calibrated sensors for ice are commercially available that can be used for relative calibration, extensive studies have been performed to use the reciprocity calibration method, that does not require a reference receiver, in ice [30]. The in-situ calibration of sensors deep in natural glacial ice is even more challenging due to the limited possibilities of access to the detectors.

In the SPATS project (cf. next section) it has been tried to factorize the problem in the laboratory: SPATS sensors have been absolutely calibrated in water at 0°C before deployment [31] and the angular response of the sensor has been determined at different frequencies [32]. It is not obvious whether the calibration results can be transferred to operation conditions, where the sensors are frozen in the deep ice at South Pole. There, they are subject to low temperatures of approx. −50°C, increased static pressure, and a different sensor-medium interface (ice to steel). The different effects have been studied separately in the laboratory:

- In air at constant pressure, a sensor has been cooled down from 0°C to −50°C and its response to the signal from an external transmitter, kept at constant temperature, has been used as an estimator for the receiver sensitivity. It has been found that the sensor sensitivity increases by a factor of 1.5 ± 0.2 when the temperature was lowered from 0°C to −50°C [31].
- In a pressure vessel, filled with an emulsion of water and oil, a sensor has been exposed to static pressure up to 100 bar. A transmitter placed outside the pressure vessel and transmitting through the steel vessel has been used to determine possible changes in sensitivity. The results indicate that the variation of the receiver sensitivity is less than 30% between 1 and 100 bar static pressure [31].
- The Aachen Acoustic Laboratory [23] allows for the production of volumes up to 3 m^3 of clear ice with temperatures down to −25°C which are ideal for the study of changes in sensor sensitivity when going from the water to the ice phase. Figure 2 shows the ratio of the sensitivities of a SPATS sensor measured in water and ice using the reciprocity calibration method. It can be seen that the ratio is compatible with unity within its errors, indicating that the sensitivity does not change in the frequency range relevant for acoustic neutrino detection (approx. from 10 to 50 kHz) when the sensor is frozen into bulk ice.

Assuming that the influences of the environmental effects are independent, it has been concluded that for the SPATS sensors the sensitivity in ice will be increased by a factor of 1.5 ± 0.4 compared to the pre-deployment calibration in water [34]. This factor takes into account the uncertainties from the temperature and pressure measurements.

It is under investigation how naturally occurring transient noise events and artificial calibration transmitters can be utilized for sensor relative calibration and angular response measurements in-situ [35].

SITE EXPLORATION

Another important step towards a large scale detector embedded in a natural detection medium is the full understanding of the signal propagation properties and backgrounds therein. For an acoustic experiment this means the determination of the sound speed depth profile, the attenuation length, the noise level, and possible transient backgrounds. The sound speed profile determines possible refraction during the signal propagation that impedes accurate vertex reconstruction up the existence of multiple solutions. The attenuation length and noise level will determine the detector geometry required to achieve a given neutrino energy threshold. Transient noise sources need to be identified and characterized to separate them from neutrino induced events. The measurement of the sound speed profile and transient backgrounds are easier to accomplish in the sense that they only rely on time information. The attenuation length and noise level measurement depend on amplitude informa-

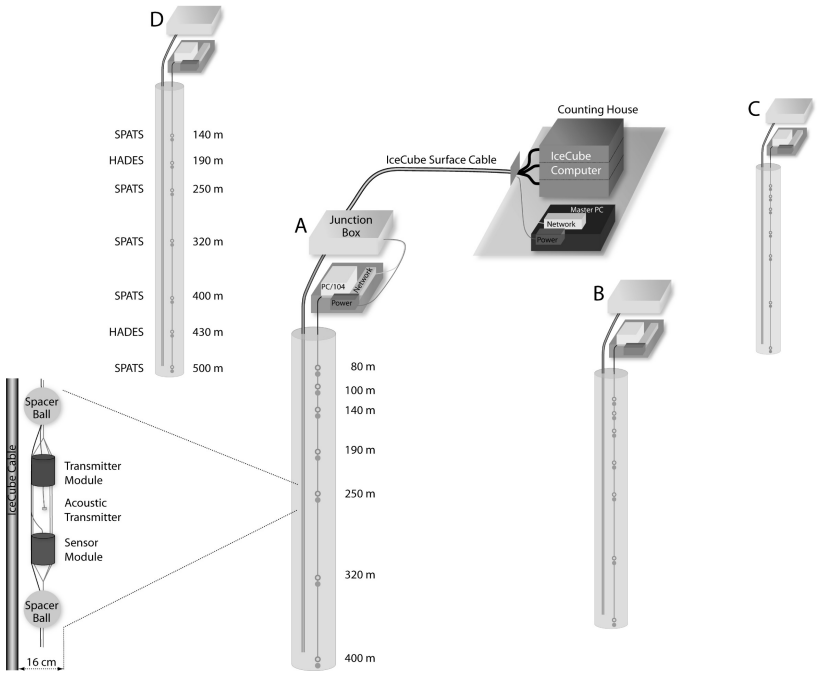


FIGURE 3. Overview of the South Pole Acoustic Test Setup (SPATS) frozen into the upper 500 m of holes drilled for the IceCube neutrino telescope (from [31]).

tion and are thus subject to the calibration challenge discussed in the previous section.

SPATS – Hardware

To carry out these measurements in the Antarctic ice at the South Pole, the site of the IceCube neutrino observatory, the South Pole Acoustic Test Setup (SPATS) has been designed and is successfully operated since January 2007 [31]. SPATS consists of four vertical strings that are deployed in the upper 500 m part of IceCube bore holes after the installation of the optical IceCube string. Horizontal baselines between 125 m and 543 m are covered. Each SPATS string is instrumented with seven stages, each containing an acoustic receiver and a transmitter. The SPATS sensor is made from a steel housing with three piezoceramic disks pressed to the inner wall at 120° separation for full azimuthal coverage. The signals are amplified in the sensor module and the differential analogue signal is transmitted via twisted pair cable to the surface where it is digitized and time stamped in a String-PC. The data from all four strings are collected by a Master-PC housed in the IceCube counting house and are prepared for satellite transmission to the IceCube central data storage. At two positions an alternative sensor type, HADES, is installed, where the piezoceramic element is cast in resin and mounted below the steel housing. HADES is used for systematic studies of the sensor medium coupling. The SPATS transmitter consists of a piezoceramic ring cast in resin and frozen directly into the ice. It is connected to a high voltage pulser which is protected in a steel housing and steered by the String-PC. A schematic overview of the SPATS hardware is shown in Fig. 3.

SPATS is complemented by a mobile acoustic transmitter, called “pinger”, which can be lowered into freshly drilled water filled IceCube holes while continuously emitting acoustic pulses with high stability. The pinger is retrieved from the hole after operation.

SPATS – Results

SPATS has measured the speed of sound depth profile in the Antarctic ice at the South Pole in the depth range from 80 m to 500 m using the retrievable pinger over horizontal baselines of 125 m [37]. The pinger emits longitudinal waves that propagate through the water column in the drill hole and are then transmitted into the ice. When the incidence on the water-ice interface is non-normal, part of the waves energy is transferred into a shear wave. Thus, the sound speed profile for pressure and shear waves could be determined. The speed of sound is found to be increasing in the top 200 m of the ice where a gradual transition from a snow/air mixture occurs (firn layer)

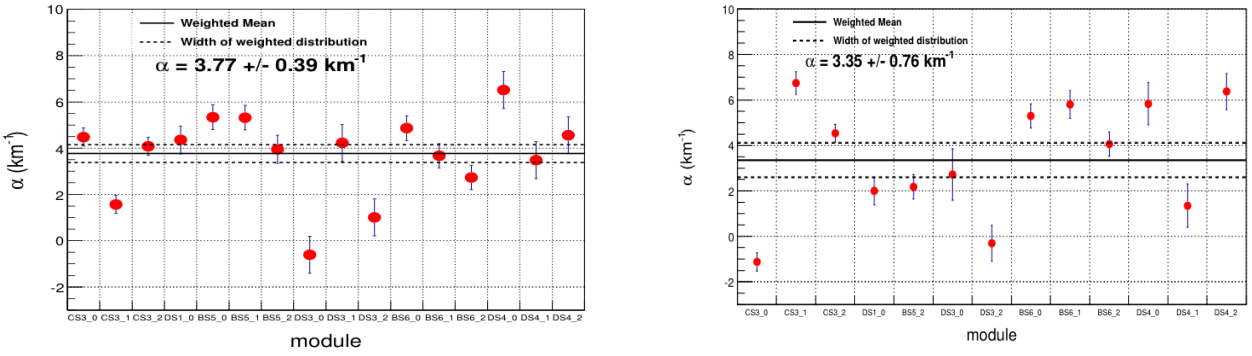


FIGURE 4. Acoustic attenuation coefficient for 30 kHz (left) and 45 kHz (right) measured with the SPATS retrievable pinger in different sensor channels (from [36]).

and is found to be constant below that depth. The best fit values [37] for the sound speed v at 375 m depth and its gradient g at this depth are for pressure waves

$$\begin{aligned} v_p &= (3878 \pm 12)\,\mathrm{m\,s^{-1}} \\ g_p &= (0.087 \pm 0.13)\,\frac{\mathrm{m\,s^{-1}}}{\mathrm{m}} \end{aligned}$$

and for shear waves

$$\begin{aligned} v_s &= (1975.8 \pm 8.0)\,\mathrm{m\,s^{-1}} \\ g_s &= (0.067 \pm 0.086)\,\frac{\mathrm{m\,s^{-1}}}{\mathrm{m}} \end{aligned}$$

Since the gradient is compatible with zero only very little refraction is expected below the firn layer.

Pinger data have also proven very valuable to determine the signal amplitude attenuation length [38] in the frequency range from 10 to 30 kHz. This analysis requires the comparison of the signal observed at different distances. To reduce systematic uncertainties from the sensor absolute calibration and angular response, attenuation lengths are derived for each sensor channel. For this the pinger, which produces highly reproducible pulses, is deployed in different IceCube drill holes at increasing distances, but aligned in direction, so that only a small range of the angular response of the sensor is probed. Averaging over all available sensor channels leads to an signal amplitude attenuation length [38] of

$$\langle \lambda \rangle = 312^{+68}_{-47}\,\mathrm{m}$$

This value is much smaller than the several kilometers initially expected from theoretical calculations [25]. To study this discrepancy a modified pinger has been constructed that emits gated sine bursts at different frequencies (30, 45, and 60 kHz). It has been used to study the frequency dependence of the attenuation length. Absorption, if it would be the main attenuation mechanism, is expected to be frequency independent, whereas the scattering coefficient would increase $\propto f^4$, where f is the frequency of the signal [25]. The data from the modified pinger are analyzed with the same methods as described above [36]. Figure 4 shows the attenuation coefficient measured in the different sensor channels for 30 kHz and 45 kHz as well as the mean value and spread of the data points. The signal-to-noise ratio for 60 kHz has been too poor to extract an attenuation length since the transmit response of the pinger piezoelectric element is small at this frequency. It can be seen that the two values are compatible with a frequency independent attenuation length and that an f^4 frequency dependence is hard to reconcile with the data.

SPATS unbiased noise data, that are recorded every hour for 0.1 s have been used to study the background noise level. It has been shown that the noise is Gaussian and that the RMS is very stable over time [34]. Using the corrections on the sensor calibration discussed in the previous section, the absolute noise level below the firn layer has been estimated to be 14 mPa, corresponding to the signal expected from a 10^{11} GeV neutrino interacting at a distance of 1000 m to the sensor [34]. However, the systematic uncertainty on the noise level is still large, making additional measurements with sensors pre-calibrated in ice desirable.

An analysis of transient events triggering all four strings of the SPATS detector revealed only man-made sources: all events were reconstructed to either refreezing IceCube drill holes or Rodriguez Wells, large caverns in the ice used to circulate the water for the IceCube hot water drill system [34]. The absence of unidentified transient noise sources in the deep ice allowed setting an upper limit on the flux of ultra-high energy neutrinos. Figure 5 compares the limit set by SPATS to other experiments and the expected cosmogenic neutrino flux.

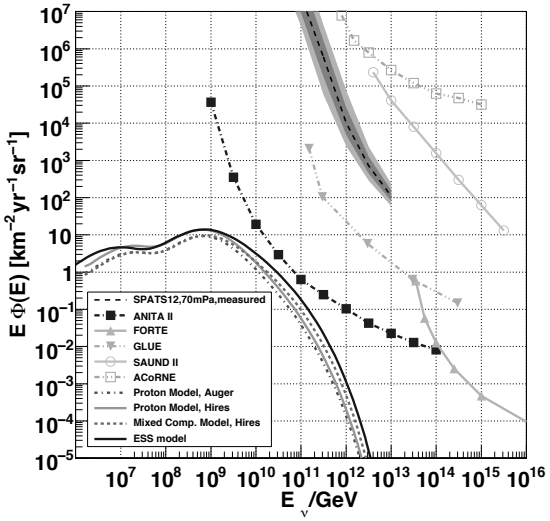


FIGURE 5. Upper limits (90% C.L.) on the all-flavor flux of ultra-high energy neutrinos set by acoustic neutrino detection experiments in water (SAUND II, ACoRNE) and ice (SPATS12). Several models on for the flux of cosmogenic neutrinos and the most stringent limits set by radio experiments are shown for comparison (adapted from [34]).

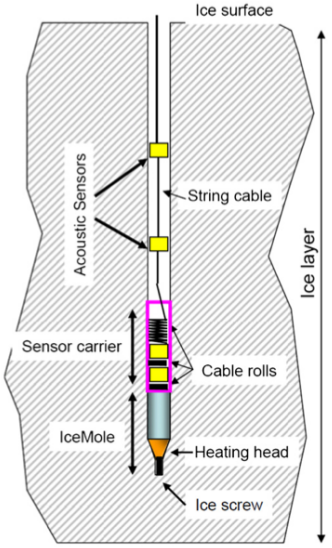


FIGURE 6. Schematic of an autonomous drilling and deployment probe based on the IceMole concept (cf. text). The cable and sensors are stored in and deployed from the probe, so that the hole is allowed to refreeze immediately after the passage of the probe (from [39]).

It has to be kept in mind that none of the acoustic experiments shown there were designed as neutrino detectors, but were built for site-exploration (SPATS) or parasitically use existing military hydrophone arrays to search for neutrino induced signals (SAUND II, ACoRNE).

A PATH FORWARDS

The SPATS results show that acoustic neutrino detection in the glacial ice at the South Pole is feasible. The acoustic attenuation length is shorter than for radio signals but of comparable magnitude which opens the possibility to design a hybrid radio/acoustic detector. Due to the intrinsically higher energy threshold of the acoustic technique a possible scenario is to use the radio sub-array to trigger the acoustic sub-array up to energies where the acoustic detector becomes fully efficient by itself. In this case a single in-time hit in an acoustic sensor can already be highly significant since all known backgrounds produce either only radio emission or only sound emission.

The construction of such a detector at the South Pole will require the deployment of a few hundred strings per 100 km^2 instrumented area (estimating a spacing of 500 m between strings based on the measured attenuation lengths for radio and acoustic) reaching below the firn layer. A design which is scalable in size is desirable so that, once the magnitude of the flux of ultra-high energy neutrinos is measured, the detector can be expanded in size to accumulate sufficient event statistics to answer the physics questions discussed in the introductory section.

A strong R&D program will be required to realize a new large area hybrid detector. Apart from South Pole there are several other sites in Antarctica where scientific infrastructure exists and which are worth evaluating:
- On the Ross Ice Shelf the ARIANNA radio neutrino detector[1] is currently under construction.
- Concordia Station at Dome C is located on top of more than 3 km of very cold ice which is favorable for acoustic and radio signal propagation.

The installation of a new detector consisting of several hundred to a few thousand strings will also require new techniques for drilling and deployment. One possibility that is being discussed is the use of autonomous drilling- and/or melting-probes similar to the IceMole [40] prototype. To minimize human intervention in the drilling and deployment procedure, the sensors and cable would be stored in and deployed from the disposable icecraft which would remain in the ice at the bottom of the string after deployment. This allows for the hole to refreeze immediately after the passage of the probe. A schematic of the procedure is shown in Fig. 6.

A large area detector at a remote site will also require new concepts for calibration, communication and power

[1] http://arianna.ps.uci.edu/

supply. The large overall extent and the large distances between the components prohibit a fully cabled design. Wireless data transmission and power generation at the site of the component by e.g. wind or solar power are required. Ideally one would have a combination of wind and solar power since beyond the polar circles solar power is unavailable half of the year. Valuable lessons can be learned from large area experiments which are already in operation, like the Pierre Auger Observatory [41].

CONCLUSIONS

Ultra-high energy neutrinos offer a vast physics program covering astrophysics, cosmology, particle physics, and physics beyond the Standard Model. The acoustic neutrino detection technique has made large advances over the last few years: sensors have been designed and their behavior in ice is largely understood. The acoustic properties of the South Pole glacier have been measured and found to be suitable for neutrino detection. It is expected that acoustic can play an important part in a future hybrid neutrino telescope in ice. To realize this a strong R&D program has to be established and first promising studies have already been presented.

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