



Status and recent results of the South Pole Acoustic Test Setup

THE ICECUBE COLLABORATION¹

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Abstract: The feasibility and design of an acoustic neutrino detection array in the South Pole ice depend on the acoustic properties of the ice. The South Pole Acoustic Test Setup (SPATS) was built to evaluate the acoustic characteristics of the ice in the 10 to 100 kHz frequency range. SPATS has been operating successfully since January 2007 and has been able to measure or constrain all parameters. Recent results including the absolute noise measurement of the South Pole ice, the SPATS sensor calibration, and the frequency dependence of attenuation length are presented.

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1 Introduction

The detection of ultra-high energy neutrinos of extraterrestrial origin is a big challenge because of their low flux and small interaction cross-sections. To detect the cosmogenic or Greisen-Zatsepin-Kuzmin (GZK), neutrinos of energy 10^{17-20} eV produced by ultra-high-energy cosmic rays interacting with the cosmic microwave background radiation, a detector with effective volume in the order of 100 km^3 is needed. Such a large volume is necessary since the estimated rate of GZK neutrino induced showers is on the order of $0.1 \text{ km}^{-3} \text{ yr}^{-1}$ [1, 2].

The interactions of high energy neutrinos in ice produce optical [3], radio [4], and acoustic radiation [5], each of which therefore provides a possible method of detecting the neutrinos. Both radio and acoustic signals have attenuation lengths that are larger than in the optical signals [6].

While the optical method is well understood and calibrated with atmospheric neutrinos, the density of instrumentation required makes it prohibitively expensive to scale to a 100 km^3 detector size. The acoustic and radio methods, on the other hand, can in principle be used to instrument a large volume sparsely and achieve good sensitivity per cost in this energy range [8].

South Pole ice as a medium is predicted to be especially well suited for acoustic detection of extremely high-energy neutrinos [7]. To test the theoretical estimates, the South Pole Acoustic Test Setup (SPATS) was deployed at the South Pole. The main purpose of SPATS is to measure the acoustic attenuation length, sound speed profile, noise

floor, and transient noise sources in situ at the South Pole. Measurement of these parameters will allow us to obtain a realistic sensitivity estimate for a possible future acoustic neutrino telescope in the Antarctic ice.

2 SPATS Array

The South Pole Acoustic Test Setup consists of four vertical strings that were deployed in the upper 500 meters of selected IceCube holes to form a trapezoidal array, with inter-string distances from 125 to 543 m [9]. Each string has 7 acoustic stages, each stage is comprised of a sensor and a transmitter. The transmitter module consists of a steel pressure vessel that houses a high-voltage pulse generator board and a temperature or pressure sensor. Triggered HV pulses are sent to the transmitter, a ring-shaped piezo-ceramic element that is cast in epoxy for electrical insulation and positioned 13 cm below the steel housing. The motivation of using ring-shaped piezo-ceramics is to obtain an azimuthally isotropic emission. The actual emission directivity of such an element was measured in the azimuthal and polar directions [10]. The sensor module has three channels, each 120° apart in azimuth, to ensure good angular coverage.

A retrievable pinger was also deployed in 13 water-filled IceCube holes: 6 holes were pinged in December 2007-January 2008 and 7 more holes were pinged using an improved pinger design; 4 in December 2008-January 2009 and 3 in December 2009-January 2010. In 2009/2010, the pinger was modified to emit lower bandwidth pulses at

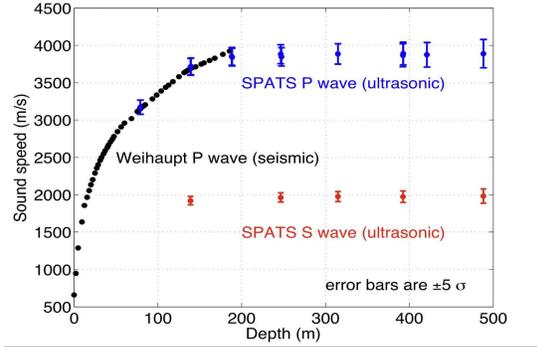


Figure 1: Sound speed for both pressure and shear waves, at ultrasonic frequencies, versus depth in the South Pole ice. A previous measurement, made by Weihaupt, at seismic (Hz) frequencies is shown for comparison [11].

three well defined frequencies (30, 45, and 60 kHz) and deployed in three boreholes going down to 1000 m depth. The measured data is used to study the frequency dependence of the attenuation length, as well as the speed of sound on inclined paths.

3 Results

3.1 Sound speed

The speed of both pressure waves and shear waves are measured in the dense ice between 80 m and 500 m as a function of depth using the SPATS pinger setup [11], and were found to be 3878 ± 12 m/s and 1975.8 ± 8.0 m/s, respectively. The resulting vertical sound speed gradient for both pressure and shear waves is consistent with no refraction between 200 and 500 m depth as shown in Fig. 1. These results have encouraging implications for neutrino astronomy: the negligible refraction of acoustic waves deeper than 200 m indicates that neutrino direction and energy reconstruction, as well as separation from background events, could be done easily and accurately.

3.2 Properties of noise floor

The energy threshold for the detection of acoustic signals from ultra-high energy neutrino interactions depends strongly on the absolute noise level in the target material. SPATS has monitored the noise in Antarctic ice at the geographic South Pole for more than two years down to 500 m depth. The noise is very stable and Gaussian distributed as shown in Fig. 2 [12]. The resulting noise level for all operative SPATS channels is presented in ref. [12]. The contribution from electronic self-noise that has been measured in the laboratory prior to deployment is found to be 7 mPa. Subtracting this contribution quadratically from the measured mean noise level leads to an estimated mean noise level in South Polar ice of 20 mPa above 200 m and 14 mPa

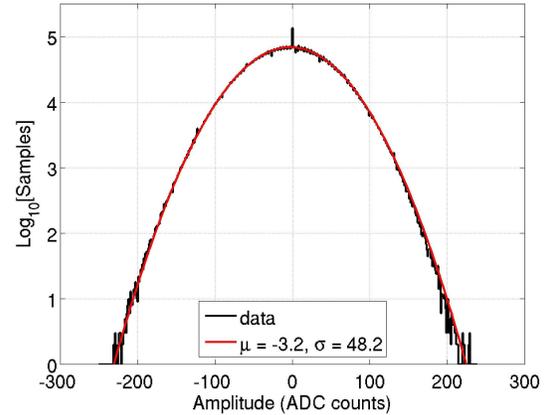


Figure 2: An example for the South Pole noise floor recorded by one of the SPATS sensors.

below 200 m integrated over the frequency range relevant for acoustic neutrino detection of 10 to 50 kHz. The origin and significance of the decrease in the noise level with depth remains unclear. One possible qualitative explanation for the observed depth dependence is a contribution of noise generated on the surface. Due to the gradient in the sound speed with depth [11], all noise from the surface will be refracted back towards the surface, thus shielding deeper regions from surface noise.

3.3 Transient noise events

Using a threshold trigger mode for the active SPATS channels and offline coincidence window of 200 ms, corresponding to a pressure wave with the longest distance across the SPATS array of approximately 775 m, the vertex of transient events producing triggers on all four strings is reconstructed using an idealized global positioning system algorithm [12]. The horizontal positions of all reconstructed vertices are shown in Fig. 3. SPATS registered acoustic pulse-like events in the IceCube detector volume and its vicinity. All sources of transient noise are well localized in space and have been identified as being man made; IceCube boreholes re-freezing after the deployment of the optical module produce cracking noise for a period of about 20 days. Rodriguez Wells, caverns melted in the ice at a depth of 50-100 m as a water source for IceCube drilling, also produce a cracking noise during refreezing.

The acoustic signals from refreezing IceCube holes and from anthropogenic sources have been used to localize acoustic events. The absence of any transient events observed from locations other than known sources allows us to set a limit on the flux of ultra high energy ($E_\nu > 10^{20}$ eV) neutrinos. Fig. 4 shows the neutrino flux limit of the 2009 SPATS configuration (70 mPa threshold, ≥ 5 hits per event) compared to different neutrino flux limits [12].

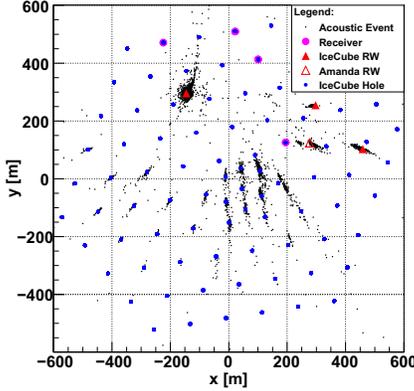


Figure 3: The vertex position for all transient events recorded since August 2008 in the horizontal plane of the the IceCube coordinate system, see the original figure from Ref. [12].

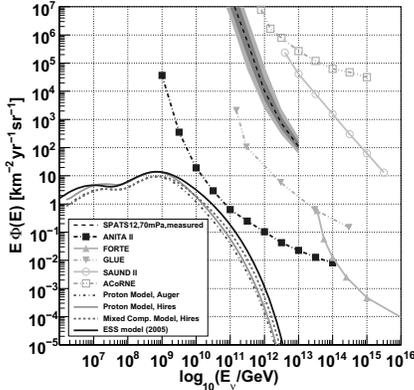


Figure 4: The neutrino flux limit of the 2009 SPATS configuration (70 mPa threshold, ≥ 5 hits per event), for the detailed description of the limits see Ref. [12].

3.4 Attenuation length

Measuring the attenuation length requires the comparison of signal amplitudes or energies after different propagation lengths through the ice. To achieve this, the 2008/2009 pinger was equipped with mechanical stabilizers, in order to keep the pinger close to the central axis of the hole. Centralization of the pinger minimized pulse to pulse variations caused by different signal transmission characteristics at the water-ice interface. The pinger emission rate was increased from 1 Hz (used in the previous season) to 10 Hz in order to improve the signal to noise ratio.

The data sets from 2008/2009 were analyzed using different sound sources, the pinger, the frozen-in SPATS transmitters and transient signals from freezing IceCube holes to determine the attenuation length. To minimize the uncertainties due to different sensitivity of the sensors and

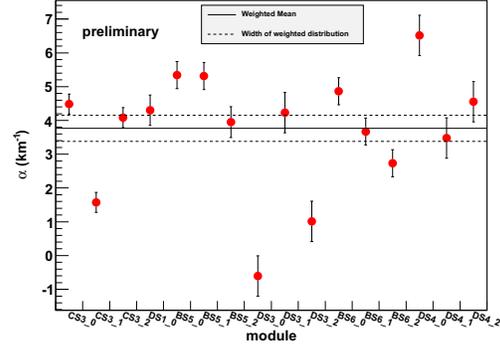


Figure 5: The attenuation coefficients with standard error for different SPATS sensors at 30 kHz.

unknown angular response, the attenuation length was determined with each sensor individually placing the sound source at different distances to the receiver, while trying to keep the same direction seen from the sensor. All methods consistently deliver an attenuation length of about 300 m with a 20% uncertainty [13]. These measurements observed a weak frequency dependence below 30 kHz. This result is in strong contradiction with the phenomenological model prediction of 9 ± 3 km with absorption as the dominant mechanism and negligible scattering on ice grains [7].

To investigate this discrepancy the pinger was modified for the 2009/2010 Pole season to allow us to measure the attenuation length at different frequencies from 30 kHz to 60 kHz. The result will help to discriminate between different contributing attenuation mechanisms: the scattering coefficient is expected to increase with f^4 while the absorption coefficient should be nearly frequency independent. The modified pinger was successfully deployed in three IceCube holes aligned with respect to the SPATS array at horizontal distances between 180 m and 820 m and delivered high quality data.

Each waveform consists of six pulses, two sets of 3 pulses in a (30,45,60) kHz cycle. The energy contribution from the noise-subtracted waveform was calculated at each frequency in order to calculate the attenuation coefficient as explained in [13]. Fig. 5 shows the attenuation coefficient as obtained from the available horizontal pinger-sensor configuration at a frequency of 30 kHz. The data points scatter more than their error bars indicate, implying that there are additional systematic uncertainties, e.g. arising from local ice properties or the interface between the hole ice and the sensors. The error represents the spread between attenuation lengths measured with each sensor. The weighted mean for the attenuation length is 266 ± 27 m at 30 kHz and 300 ± 88 m at 45 kHz. The contribution of 60 kHz is not strong enough at large distances to calculate the attenuation length. The measured attenuation length at 30 and 45 kHz is independent of the frequency within the uncertainties. Because Rayleigh scattering depends on grain

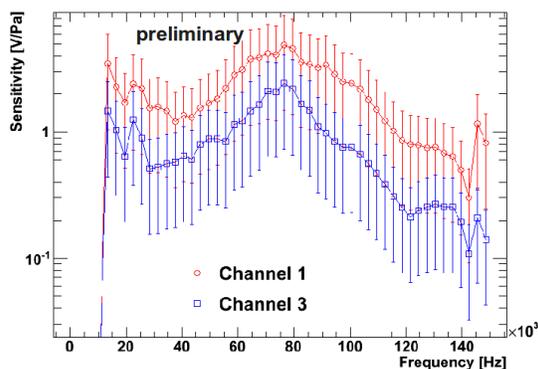


Figure 6: Absolute sensitivity in ice for two different SPATS sensor-channels

diameter and frequency, the measured attenuation length at the South Pole is not dominated by scattering.

3.5 SPATS sensor calibration

The SPATS sensor calibration was performed in the Aachen Acoustic Laboratory (AAL) as a complement to the in-situ test at South Pole with SPATS [14]. Sensor absolute sensitivity was measured in water and in ice using reciprocity calibration [15]. For this method, no absolute calibrated receiver is needed as reference. Fig. 6 shows the absolute sensitivity for two different SPATS sensor-channels in ice.

4 CONCLUSIONS

The South Pole Acoustic Test Setup has been operated successfully since January 2007 and has been able to measure or constrain all South Pole acoustic ice parameters. We presented the latest results from SPATS including:

- The sound speed depth profile was measured in deep ice and found to be consistent with a constant sound speed below 200 m depth. Further analysis is underway including inclined paths. This will allow us to probe the fabric of the ice because the sound speed can vary from site to site due to the difference in the crystal grain orientation.
- The absolute noise at the South Pole is very stable and Gaussian distributed. The measurements of the absolute noise level allow us to put a threshold for a future acoustic neutrinos detector at South Pole which depends on the noise level.
- SPATS identified sources for the transient noise, acoustic pulse-like events, in the IceCube detector volume and its vicinity.
- The attenuation length including the recent multi-frequency measurements is presented. The measurements do not show a strong depth dependency. The

attenuation length, which seems not to depend on scattering, has been found to be about 300 m. This is less than expected from theory. However, for 10^{18} eV neutrinos, the typical distance over which they can be detected is reduced only by a factor of about 2.

- A SPATS sensor has been absolutely calibrated by the reciprocity method in ice.

SPATS is continuing to take data. An upgrade of the DAQ software to read out all sensor channels simultaneously and to form a multiplicity trigger online, will increase the detector sensitivity. SPATS results show that the acoustic detection technique represents a promising tool to build a large hybrid (acoustic/radio) neutrino telescope in the South Pole ice. Individual hits from an acoustic array operated synchronously with a radio array could still be valuable. The coincidence between radio and acoustic hits could provide much-needed confirmation about the direction and energy reconstruction of the events.

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