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The South Pole Acoustic Test Setup: calibrations and lake test.

S Böser¹, C Bohm³, F Descamps^{1,5}, J Fischer¹, A Hallgren⁴,
R Heller¹, S Hundertmark³, K Krieger¹, R Nahnauer¹, M Pohl¹,
P B Price², K Sulanke¹ and J Vandenbroucke²

¹ DESY, Platanenallee 6, D-15738 Zeuthen, Germany

² Dept. of Physics, University of California, Berkeley, CA 94720, USA

³ University Stockholm, Fysikum, SE-106 91 Stockholm, Sweden

⁴ University Uppsala, Department of Radiation Sciences, Box 535, SE-751 21 Uppsala, Sweden

⁵ On leave of absence of University of Gent, Belgium

E-mail: Freija.Descamps@ugent.be

Abstract. In order to detect the small neutrino fluxes expected at ultra-high energies, large volumes of materials have to be instrumented with inexpensive but sensitive acoustic sensors. The South Pole Acoustic Test Setup (SPATS) will be installed in the Antarctic ice during the polar season 2006/2007 after which the collected data will be used to reveal the acoustic properties of the South Polar ice cap. The developed piezoceramic based ultrasound sensors and transmitters that are part of this system have been extensively studied during calibration measurements in water, using a commercial hydrophone as reference. Also, a SPATS system test was accomplished in Lake Torneträsk, Abisko (Sweden). This allowed verification of the DAQ system, transmitter range and sensor performance. Here the results of the calibrations and the Abisko lake measurements are reported.

1. Introduction

Currently, the field of neutrino astrophysics in the 10^{12} to 10^{15} eV energy range is in fast progress. Different experiments are running or being constructed in order to detect neutrinos of that energy region by Čerenkov light emission of secondary particles produced in neutrino-nucleon interactions. The affordable size of such detectors is limited by the absorption length of Čerenkov light in the detector medium, which is $\sim 10^2$ m in the case of ice.

In order to observe the very small predicted neutrino fluxes at the higher energies of 10^{17} to 10^{20} eV with reasonable statistics, new detection methods are needed to instrument the required larger detector volumes at reasonable cost. A possible solution lies in acoustic neutrino detection, which was described in [1]. The principle is based on the fact that a bipolar pressure wave results from the produced particle cascade in high energetic neutrino-nucleon interactions. It has a typical expected frequency of around 20 kHz and propagates perpendicular to the cascade axis, allowing good direction reconstruction. Since sound waves with frequencies between 10 kHz and 100 kHz have attenuation lengths in the order of 10^3 m, depending on target material [2], the large volume of detector material can be instrumented more sparsely.

The feasibility and specific design of an acoustic neutrino detection array in the South pole ice cap depend on the acoustic properties of the ice. The absorption lengths will indicate the

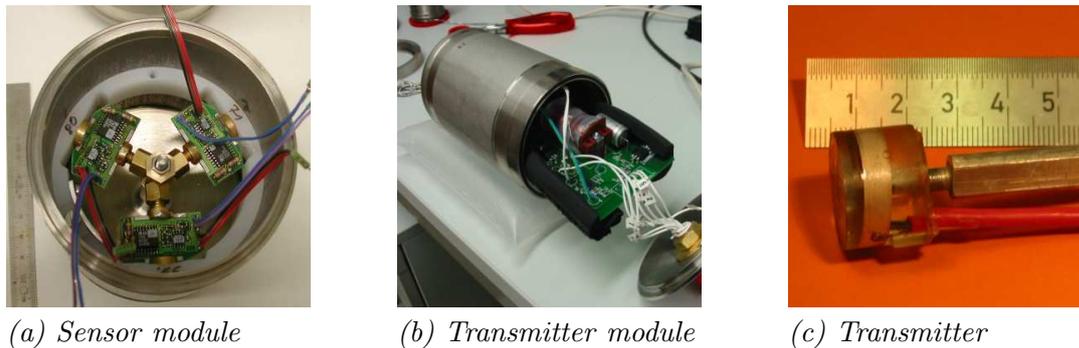


Figure 1. View of SPATS transducer components: an inner view of the sensor module (a) and transmitter module (b) where the preload screw with the amplifiers and LC circuit respectively are visible. The ring shaped ceramic (c) is cast in epoxy for electrical insulation.

optimal horizontal spacing of sensors, whereas the speed of sound and background noise level relate to the level of refraction of the surface noise and energy threshold respectively. It is also important to measure transient events in order to locate sources of background events. The South Pole Acoustic Test Setup (SPATS) has been built to evaluate these characteristics of the ice in the concerned frequency range. The measurements require production and detection of acoustic pulses at different distances and depths. For this, custom-made acoustic transducers will be used.

2. The South Pole Acoustic Test Setup

The South Pole Acoustic Test Setup consists of three vertical strings to be deployed in the upper 400 meter of the ice cap where the variation of acoustic properties is expected to be strongest. Each string has 7 stages and each stage consists of one transmitter and one sensor module. Both are equipped with piezo ceramic elements of the type lead zirconium titanate (PZT) with a high piezo electrical constant ($d_{33} = 500 \frac{pC}{N}$) in order to produce or detect sound. In total, 25 stages have been built. A more complete description of the complete system can be found in [3].

The sensor module design (cf. figure 1(a)) is based on a steel pressure housing that holds 3 piezo ceramic elements, each with a low noise amplifier, and a voltage regulation board that provides ± 5 V and a virtual ground. The amplifier consists of three stages. A preamplifier stage and an amplifier stage, each with a mean gain factor of 100, are prior to a line driver stage. A preload screw ensures that the piezo elements are in good contact with the steel housing. The sensor module is a complex system with many different materials. The overall response is therefore not only governed by the resonance behaviour of the piezo ceramic elements, but also by the behaviour of all other present materials. Also, the individual ceramic elements are connected by the preload screw and therefore do not behave independently. All of this leads to a complex frequency response and implies the necessary calibration of all 75 individual sensor channels.

The transmitter electronics is also located in a steel pressure housing (cf. figure 1(b)). It contains a LC circuit which provides half sinusoidal high voltage pulses of 1000 V in $10 \mu s$. The housing also contains auxiliary sensors for temperature or pressure measurements. The high voltage pulse is triggered by a TTL signal and sent to a ring shaped piezo ceramic element that is cast in epoxy for electrical insulation (cf. figure 1(c)) and positioned ~ 13 cm below the steel housing. The stability of the discharged high voltage pulse has been evaluated; it can be stated that all high voltage generators in the SPATS transmitter modules work stable and similar. A read back system will allow us to take into account observed variations that are due

to temperature differences. After deployment in the ice the ring transmitters will have arbitrary azimuthal alignment and a possible tilt in polar direction. Any angular variation in emission will therefore induce a systematic error and needs to be investigated.

3. Sensor and transmitter calibration

3.1. Reference hydrophone calibration

In order to determine absolute values of frequency dependent sensitivities, a reference with known absolute sensitivity is necessary so that the pressure spectrum of an acoustic field can be obtained. The *SENSORTECH-SQ03* has a working range from 1 Hz up to 65000 Hz and was delivered with a nominal frequency independent sensitivity of -163.3 ± 0.3 dB re. 1 V/ μ Pa. The recalibration was done using the gated burst method and gave as a result a sensitivity of -167.5 ± 0.3 dB re. 1 V/ μ Pa, i.e. a 38% decrease 3 years after production. The hydrophone threshold, i.e. the minimal detectable acoustic signal, is given by the ratio of the self noise spectrum over the sensitivity spectrum and is also called the equivalent noise level. The hydrophone frequency dependant equivalent noise levels range from 110 mPa up to 170 mPa. The frequency response was found to be rather flat for frequencies from 10 kHz up to 80 kHz and the measured variation in sensitivity with respect to azimuth was very small.

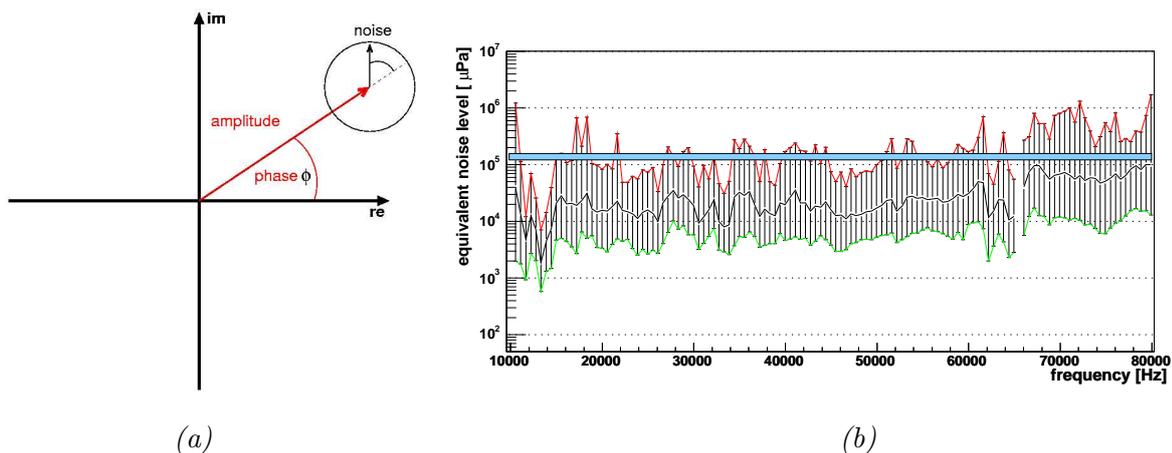


Figure 2. The schematic construction in the complex plane with amplitudes A and phase ϕ (a). Equivalent noise level of all SPATS sensor module channels (b); the red and the green line indicate the highest and lowest equivalent noise level respectively. The black line in between corresponds to the mean value and the thick blue line indicates the hydrophone value.

3.2. Sensor calibration

Ring shaped piezo ceramic elements, similar to the SPATS transmitters, were used to generate a broadband pulse in the sufficiently large water tank at the *Hamburger Schiffbauversuchsanstalt* (HSVA). The acoustic devices were mounted at a depth of 2 m and the spacing between transmitter and sensor was 1.03 m to avoid near field effects. The water temperature was about 0.5° and the salinity was 7 ppt. The generated pressure pulses were recorded with the reference hydrophone and the multi-frequency pressure spectrum was derived. The SPATS sensor modules were positioned in the same acoustic field.

Because of the expected contributions of background noise, 100 pulses were recorded for all channels. The errors on the resulting signal spectrum have been calculated by dividing each recorded signal into one signal region and four off-signal regions. The noise samples are then subtracted from the signal. A discrete Fourier transform of the received signals results in fixed

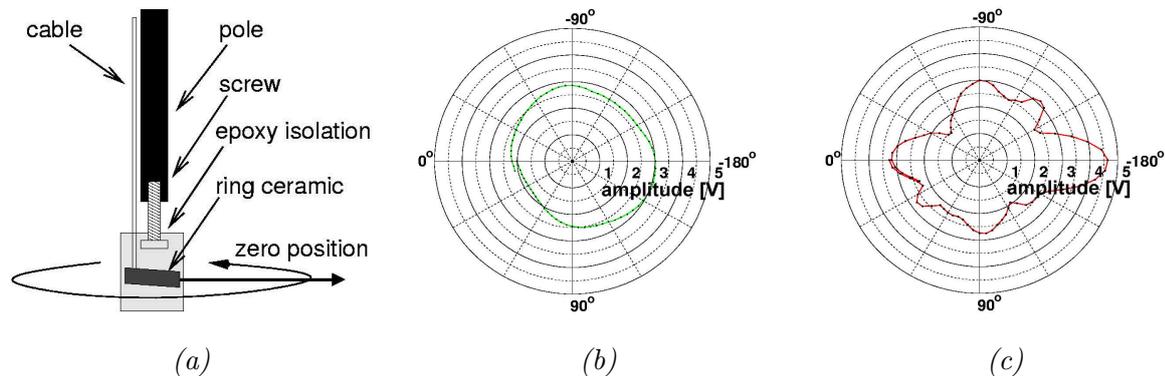


Figure 3. The setup for azimuthal directivity (a) and the results for the azimuthal (b) and polar (c) directivity of a ring shaped piezo ceramic element cast in epoxy.

amplitudes A_i and phases ϕ_i for the Fourier coefficients that are blurred by noise contributions (cf. figure 2(a)). The width of the two-dimensional gaussian σ_{signal} consists of noise contributions σ_{noise} and variations of the pressure pulse shape σ_{pulse} . From the difference of σ_{noise} and σ_{signal} it was clear that there is no significant contribution from pressure pulse variation. The signal amplitudes were derived from the Fourier coefficient distributions and the sensitivity spectra for all channels were obtained by division of the amplitude spectra over the multi-frequency pressure spectrum.

For each SPATS sensor module channel five seconds of self noise have been recorded without external influence and the self noise spectra have been derived. All self noise spectra are similar in frequency dependent noise. The equivalent noise level was obtained for all 75 channels. The average values of the equivalent noise level are between 12 mPa and 83 mPa (cf. figure 2(b)). The gap at 65.5 kHz is due to very low pressure output of the used ring transmitter at that frequency, therefore this frequency was excluded in the figure.

3.3. Transmitter calibration

Azimuthal isotropic emission is the motivation for the use of ring shaped piezo ceramics. The actual emission directivity of a ring shaped piezo ceramic was measured in azimuthal and polar direction. For measuring polar variations, the piezo ceramic was turned around the axis perpendicular to the ring axis. The setup for the azimuthal directivity measurement is shown in figure 3(a). The pulses were recorded by the reference hydrophone at a distance of 1 m.

In the final setup that will be deployed in the South pole ice, there is no control over the azimuthal orientation, so that one can expect to see variations in the amplitude of around 40% due to this systematic effect. For $\pm 10^\circ$ polar orientation uncertainty, the amplitude variation will stay below 10%.

4. Lake test

A SPATS system test was performed in lake Torneträsk in northern Sweden in April 2006 when SPATS sensors and transmitters were deployed and read out using the DAQ system. The lake was covered with about 90 cm of ice, and was between 40 m and 60 m deep at the test location. The holes were located on a straight line from north to south, where the maximum distance was about 800 m, and two holes were drilled at 400 m west and 400 m east.

The goals of this test were threefold: firstly the transmitters were tested to see variations between different modules and to demonstrate that the range is sufficient to meet SPATS requirements. Secondly, the performance of the sensor modules was compared to that of the

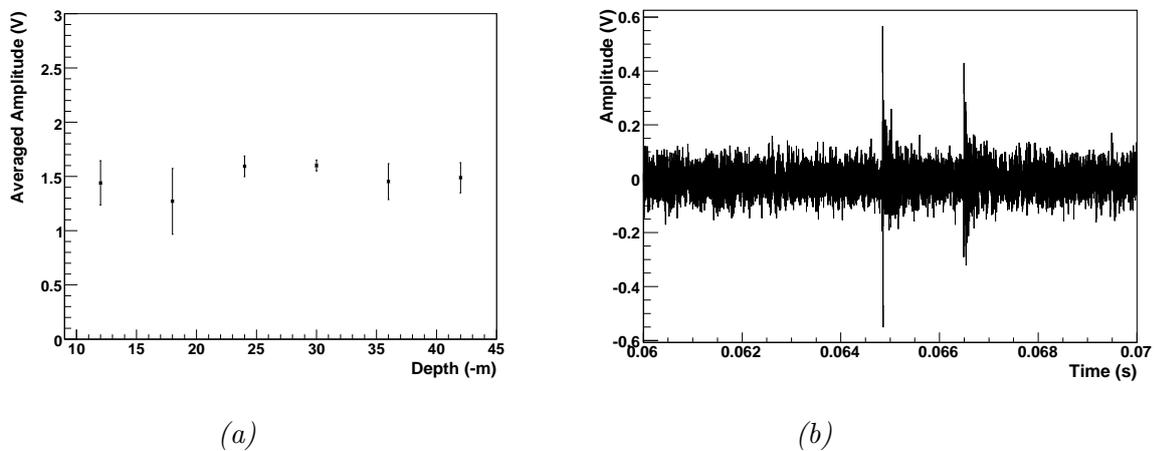


Figure 4. Results from the Abisko transmitter test: the variations in amplitude for one transmitter (a), and the transmitter signal as seen by a SPATS sensor at 800 m distance.

commercial hydrophone and the direction of the pulse was reconstructed using two channels per module. Finally, the DAQ software and hardware were tested under real deployment conditions.

For each measurement of a transmitter pulse at a certain distance and depth, 10 events were recorded by the commercial hydrophone or one of the SPATS sensors. Different effects contributed to shifts in the arrival time of the signal. Underwater currents make the devices swing or torsion in the support rope makes them spin. The signals were therefore shifted in time, so that the first amplitude maxima coincide, before extracting the mean values of the amplitudes. Lake Torneträsk was found to be a silent testing environment with a stable and low background noise level of ~ 120 mV for the SPATS sensors, excluding occasional snow scooters and strong wind.

At first, a SPATS sensor was placed at a depth of 30 m and different combinations of transmitter modules and ring shaped piezo ceramics were then lowered in a hole at 400 m distance at different depths. The amplitudes of the registered pulses were compared; an example can be found in figure 4(a). Signals from all tested transmitters are clearly visible at a distance of 400 m. The observed variations in amplitude lie within the expectations and are due to the uncertainties on azimuthal and polar orientation of the transmitter. A maximum distance of 800 m between transmitter and sensor was then achieved, where the available cable length was the limiting factor for the range test. In figure 4(b) the recorded signal with signal to noise ratio of 5 is shown. The transmitter was positioned at a depth of 20 m. There is a second pulse visible ~ 1 ms after the signal. A calculation taking into account the speed of sound profile showed that the second pulse is originating from the ice surface. Assuming an acoustic attenuation length of 1 km, an extrapolation from the signal to noise ratio gives an expected range for the SPATS transmitter in water of 1800 m.

Second, the difference in performance of the SPATS sensor and commercial hydrophone becomes clear in figures 5(a) and (b), where the significant difference in scale should be noted. The transmitter was placed at 100 m distance and 30 m depth after which the hydrophone and SPATS sensor were successively lowered to a depth of 16 m. The signal as recorded by the sensor is much stronger than that of the commercial hydrophone. In fact, the hydrophone was incapable of detecting a transmitter signal at 400 m distance at maximum gain setting.

Finally, the SPATS sensor was placed at a depth of 30 m and a transmitter was lowered to the same depth at a position 400 m north, west, south and east of the sensor location. The three sensor channels are each separated by ~ 10.5 cm of steel so that the difference in arrival time

between different channels can be observed at the maximum sampling frequency of 1.25 MHz. The orientation of the sensor module and thus the directional information was obtained by reading out two channels for each position of the transmitter.

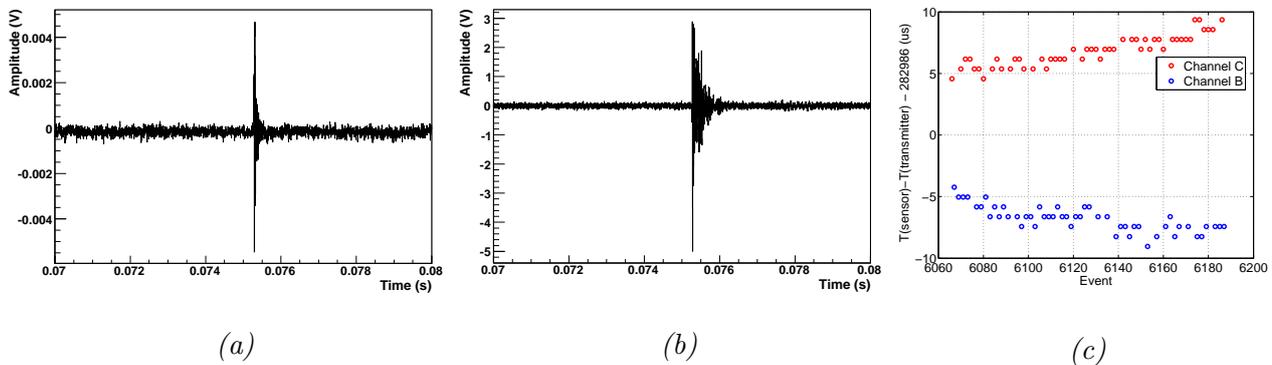


Figure 5. Sensor results from the Abisko lake test: comparison between the signals received by the commercial hydrophone (a) and SPATS sensor (b) at 100 m distance of the transmitter and the difference in transit times for two channels of a same sensor module, the increasing time difference indicates a possible spinning of the sensor module (c).

5. Conclusions

A full calibration of the SPATS sensor channels and transmitters was performed in water. The range of the mean equivalent self noise level for all 75 channels was found to be 11 mPa to 83 mPa. The azimuthal and polar variation of pulse emission of the transmitters have been quantified.

A complete system test has been accomplished during a long range test in water. The SPATS sensors and transmitters meet the requirements and the DAQ system worked 'out of the box'. The SPATS sensors were found to be more performant than the commercial hydrophone.

The different components of the South Pole Acoustic Test Setup have been tested thoroughly, and have proven to be ready for deployment in the Antarctic ice. The recorded data will reveal the acoustic properties of the ice cap in the 10 kHz to 100 kHz frequency range.

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