Angular coverage and efficiency of acoustic sensors of the South Pole Acoustic Test Setup

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Abstract. The South Pole Acoustic Test Setup consists of four strings, each instrumented with seven acoustic sensors and transmitters frozen in the upper 500 m of IceCube holes. SPATS sensors have been extensively studied in the laboratory at changing temperatures and pressure in air, water and ice. It was however impossible to create conditions like in deep ice at the acror South Pole. We present here different methods to investigate angular coverage and efficiency of the acoustic sensors after deployment. The corresponding results are used to discuss the reliability of SPATS detector measurements. We conclude with an outlook about the applicability of the described methods to future acoustic or hybrid detectors for cosmogenic neutrino measurements in ice.

Keywords: Acoustic neutrino detection, Acoustic pinger data, Acoustic sensors, SPATS
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1. INTRODUCTION

The South Pole Acoustic Test Setup (SPATS) was built to probe the potential of a large acoustic or hybrid neutrino detector array using the clear South Pole bulk ice as detection volume [1]. Therefore measuring the critical ice parameters, such as the speed of sound [2], the attenuation length [3] and the noise [4] in the South Pole ice have been crucial to rate the feasibility of cosmic neutrino detection above an energy of 10^{18} eV. Although most parameters are successfully determined the noise measurement has still large uncertainties from the sensor calibration. In-situ calibration of sensors in the ice is very difficult since the effects of low temperatures, high pressure and additional changes during the freeze-in process are unknown. Due to access limitations nothing can be said about the exact freeze-in position and the quality of the sensor coupling to the ice. Previous studies in the laboratory allow the factorization of the effect of sensitivity change due to measurements of the sensor sensitivity in water, the temperature dependence in air, the pressure dependence in water/oil and sensitivity comparison in water/ice at temperatures of 20°C at normal pressure (1 bar). Therefore in the following sections we describe new methods applied to overcome previous limitations. We study in situ the angular dependence of the sensor sensitivity using reconstructed transient events (Section 2) and use pinger data to do a relative sensor calibration (Section 3). We conclude with an outlook about use and applicability of those methods for future acoustic or hybrid detectors in Section 4.

2. STUDYING ANGULAR DEPENDENCE OF SENSITIVITY WITH TRANSIENTS

Transient events are acoustic pulses which are produced during the re-freezing process of IceCube bore holes or at Rodriguez-Well locations. Rodriguez-wells (RWs) are large caverns, around 20 m in diameter, used for the production and cycling of water for the IceCube hot water drill system. A detailed description on transient data taking, reconstruction and analysis are given in Refs. [4, 6]. Here we analyze transient data taken during the period of 28 Aug. 2008 - 20 Feb. 2009, where SPATS was running in a special configuration having two operating channels inside the same sensor module. The high quality in x-y resolution of reconstructed transient events (e.g. Hole 37: $\sigma(x) = 2.6$ m, $\sigma(y) = 5.0$ m) allows to determine the azimuthal angle of the source with respect to the sensor module. Also having different azimuthal orientation of the frozen sensors, we expect a similar response pattern of the three channels inside a sensor module due to previous laboratory tests [5]. Comparing the responses of those channels to signals from reconstructed acoustic transient events coming from different directions (Figure 1) allows to analyze their azimuthal acceptance. In the following the convention B6X stands for channel X on string B at position 6 (X=0,1,2). In Figure 2 the azimuthal distribution of localized transient events with a hit on channel B60 and/or B62 is shown. Since both channels have almost the same amount of hits from signals of the surrounding holes and Rodriguez-wells (RW), we conclude a similar angular acceptance inside the sensor module. The reduction of signals from RW07/08 at

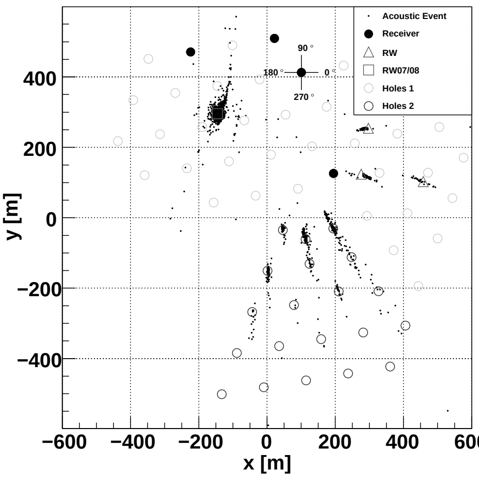

FIGURE 1. Shown are (a) the actual vertex position of all transient events recorded between August 2008 and February 2009. The sources of transient noise are the Rodriguez-wells (RW,RW07/08) and the re-freezing IceCube holes. Dark gray circles (Holes 2) indicate positions of IceCube holes drilled in this period of transient data taking and light gray circles (Holes 1) show previously drilled IceCube holes.

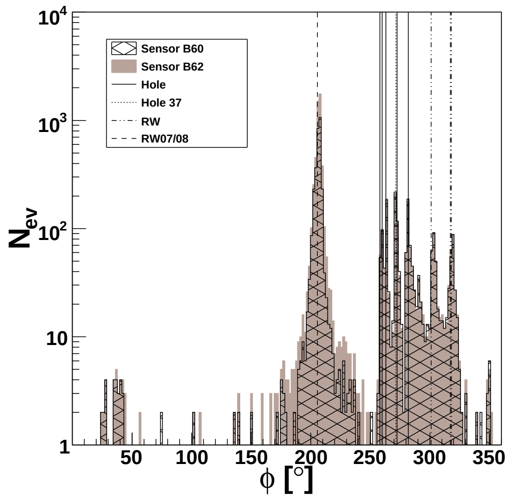

FIGURE 2. Azimuthal distribution of hits on channel B60 and/or B62, coming from localized transient events around their position (x=101.04 m, y=412.79 m).

channel B60 compared to B62 in the φ range might come from a shadowing effect as can be caused by the IceCube cable. To compare the sensitivity of both channels a signal energy (sum over squared amplitudes) for all transient events with hits at channel B60 and B62 is calculated by summing up the squared amplitudes of five time

TABLE 1. Table of pinged holes (pinger runs) within the drill period 2008/2009. The pinger run of hole 37 used in the present analysis is indicated in boldface.

Hole	x [m]	y [m]	Date	Start [UTC]	End [UTC]
28	248.2	-111.9	12.12.08	18:24	19:07
19	203.6	-228.6	16.12.08	08:29	10:11
5	237.7	-442.4	29.12.08	08:12	09:50
37	**169.4**	**-14.8**	**18.01.09**	**02:40**	**05:27**

steps (one time step = 5 μs) before and 20 time steps behind the signal onset. Figure 3 shows such a kind of power distribution encouraging the shadowing effect hypothesis since the distributions between both channels are quite similar and differences in the sensitivity between both channels can be neglected. Thus having almost the same sensitivity but a lower rate of hits at channel B60 is an indication for damping or even blocking the signal in a certain azimuthal direction. A possible reason for such a shadowing effect could be the IceCube cable next to the channel module.

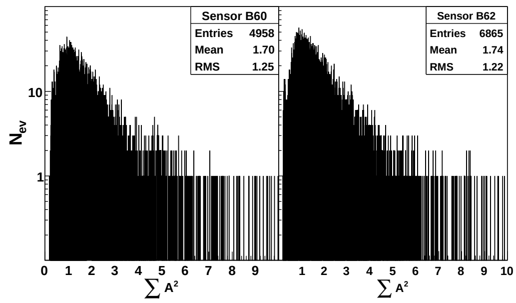

FIGURE 3. Power distribution of signals from localized transient events at channel B60 and B62.

3. RELATIVE CHANNEL CALIBRATION USING PINGER DATA

Pinger data are taken with a mobile transmitter, so called "pinger", during the drill seasons 2007/2008, 2008/2009 and 2009/2010. Since season 2008/2009 a run contains the received pinger signal from all channels at every SPATS module. Pinger data have already proven to be a valuable tool to determine the sound speed [2] and attenuation length [3] in the South Pole ice. In the following we discuss how they can be used to provide information about the sensor sensitivity and angular efficiency. In Table 1 all pinger runs done within the drill period 2008/2009 are shown. In the present analysis we use the pinger data of hole 37, the pinged hole which is closest to the acoustic strings within drill period 2008/2009, to ensure high data quality and good statistics (see Figure 4). Furthermore pinger data of hole 37 might be compa-

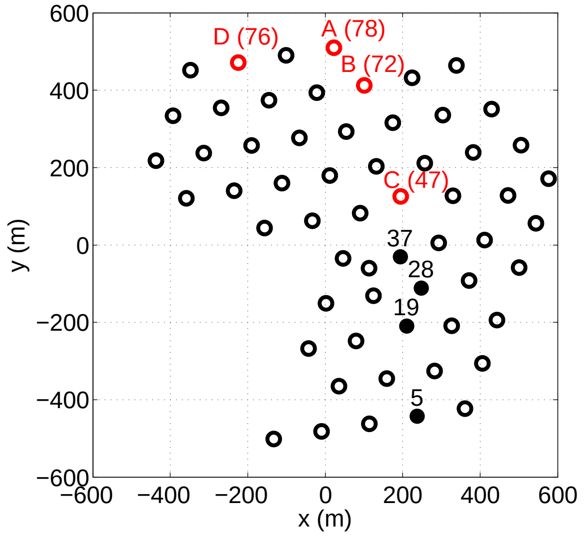

FIGURE 4. IceCube geometry after deployments in 2008/2009 [3]. Indicated are SPATS sensor strings (open red circles) and pinged holes (filled black circles).

rable with the sensor sensitivity results from transients obtained in the previous section. Pinger data taking has been done in a mode running through all sensor stations at the strings A,B,C and D in a four minutes cycle. Hence a single output file for each acoustic module is produced with the waveform of of all three channels in a sensor. The pinger pulse rate for hole 37 was 8 Hz and the time resolution of the measured signal was 5 μs. Hence 144 equally spaced (125 ms period) pulses are stored in a single pinger data file. During data taking the pinger itself moved downwards and upwards with intermediate five minute stops at a depth of 190, 250, 320, 400 and 500 meter, which are the depths of the acoustic sensors frozen in the bulk ice area. To avoid propagation effects (acoustic shear waves) and an influence of a possible layered ice structure only the data files of the sensor module in the same depth as the stationary transmitted pinger signal are analyzed. The stationary periods for the pinger run in hole 37 are indicated in Table 2. In Figure 5 a part of the stationary pinger signal obtained at the sensor module 6 (320 m depth) on string B is shown. The pinger signal can be easily identified per eye, thus 100% detection efficiency is reached for the pinger signal on all three channels. A threshold of 5.2 times the mean noise is used, which is the same value as for the transient data taking of Section 2. Hence for a relative sensor calibration only the distances from hole 37 to the different strings are important and found to be 142.73 m (C), 433.04 m (B), 544.62 m (A) and 625.09 m (D). In Figure 6 the mean squared amplitudes of received pinger signals at all channels of

TABLE 2. SPATS log book record for the pinger run at hole 37 on the 18th of January in 2009.

Depth [m]	Payout [m]	Start [UTC]	Stop [UTC]
190	202.0	03:02:31	03:08:17
250	266.3	03:11:32	03:16:56
320	340.4	03:20:20	03:25:27
400	425.2	03:29:05	03:34:21
500	530.6	03:38:42	03:46:52
400	423.2	03:51:10	03:56:26
320	337.6	03:59:30	04:04:40
250	263.3	04:07:37	04:12:55
190	200.4	04:15:38	04:20:44

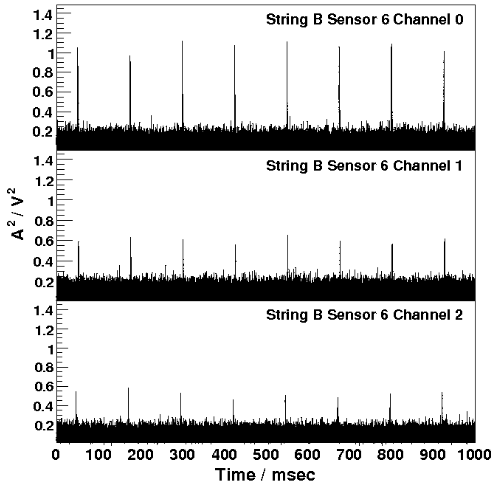

FIGURE 5. Pinger signal from hole 37 level 6 measured at the sensor module 6 (320 m depth) on string B during the stationary data taking phase.

acoustic station 6 on string B are shown. As one can see a clear distinction between signal and noise is possible and almost all pinger signals are measured at all three channels of the 433.04 m distant hole. The variety between the power distribution reflects the differences in sensitivity of all three channels, which coincide with differences between acoustic sensor channels from measurements in the laboratory. The power distribution of all three channels allows also to determine the angular sensitivity of the acoustic sensor module, if the exact freeze in position can be determined. Although showing in Figure 6 the same channels as has been used in the transient data analysis above, a direct comparison with Figure 3 is difficult due to the huge variation in signal strength and frequencies of the transient events. In Table 3 the power distribution of the acoustic pinger signals measured at the SPATS sensors are shown. Please Note: There are no SPATS sensors for String A,B and C at a depth of 500m.

TABLE 3. Mean squared amplitude of acoustic pinger signal from hole 37 measured at SPATS sensors of all acoustic strings.

		amplitude^2/ arbitr. units			
depth/m	**channel**	**str.A**	**str.B**	**str.C**	**str.D**
190	0	-	8.3	19.0	X
	1	-	3.5	87.1	X
	2	-	1.0	54.3	X
250	0	-	2.3	45.9	1.2
	1	2.1	2.4	94.3	-
	2	-	3.8	47.3	-
320	0	1.4	5.0	162.7	1.2
	1	1.2	2.1	50.8	0.9
	2	1.1	1.4	152.6	1.6
400	0	-	-	4.6	0.8
	1	-	1.0	30.9	1.0
	2	0.7	0.9	33.3	1.7
500	0	X	X	X	1.0
	1	X	X	X	1.1
	2	X	X	X	0.9

On String D in 190 m depth a different type of sensor, which is not subject to this analysis, has been mounted. Comparing all sensors, the signal strength is as expected decreasing with increasing distance. Additionally an enhancement of the relative sensitivity at a depth around 320 m, compared with the higher and lower regions can be observed. In this region the sensors with the highest sensitivity have been deployed.

4. SUMMARY AND DISCUSSION

It has been shown that pinger data can be used to determine the sensitivity of SPATS sensors after deployment and freeze-in. Therefore comparing previous studies done in the laboratory with an in-ice sensitivity analysis is an appropriate tool to study the environmental impact on the acoustic sensors to reduce uncertainties in the noise measurements. Therefore pinger data are especially important for acoustic detectors deployed in inaccessible regions with conditions not reproducible in the laboratory, like South Pole ice or permafrost soils [7]. Furthermore pinger and transient data (if transient sources exist) coming from different directions can be used to estimate the orientation of the acoustic sensors in the detector medium and their angular sensitivity. A complete detector grid with more than four acoustic strings and fixed spacings in between increases the reliability of such an analysis significantly. Pinger data can also be used to learn more about the structure of the surrounding medium, using the information of signal propagation and small run time differences along an inclined path between pinger and acoustic module. In case of a mobile pinger, as has been used for the present analysis, it is also possible to study the effect of a moving acoustic source and the influence of this propagation on the measurement. Such an analysis might give a better understanding about moving acoustic sources such as cracks in the South Pole ice. A future acoustic or hybrid detector built for neutrino detection should have transmitters deployed at each string and depth similar to the string design of SPATS. Furthermore at least at central strings a mobile transmitter run should be done, where a strong pinger signal is used to go below the deployment depth to test the homogeneity of the detector in the ice and its performance to acoustic signals coming from all directions. One has to keep in mind, that pinger studies for estimation of sound speed and attenuation length [2, 3], as done successfully at the geographic South Pole where SPATS is situated, have to be repeated at any different detector site.

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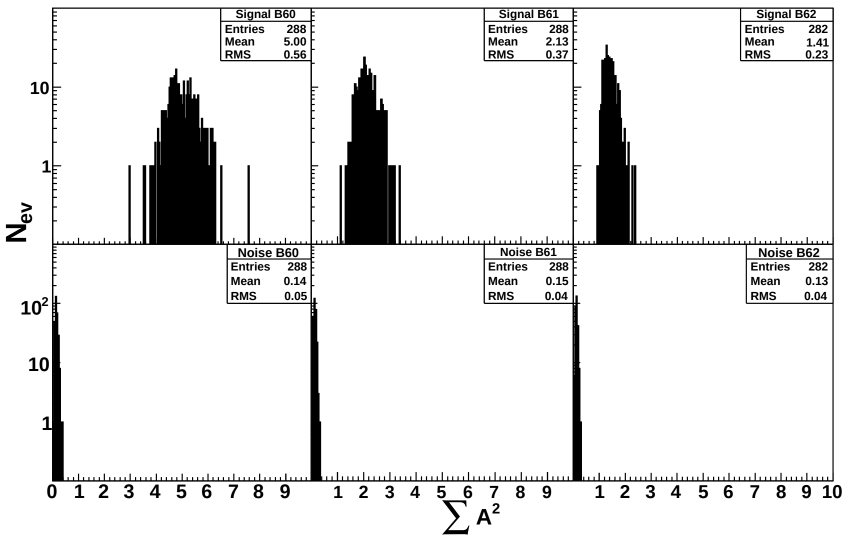

FIGURE 6. Distribution of the mean squared amplitude (power distribution) of pinger signals at all channels of the acoustic module six at string B. Here only stationary pinger signals at the same depth (320 m) are used to avoid propagation effects.