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Status of the South Pole Acoustic Test Setup

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Status of the SOUTH POLE ACOUSTIC TEST SETUP

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Abstract. Due to the low flux of ultra-high energetic neutrinos induced in interactions of cosmic rays with the cosmic microwave background, very large instrumented volumes and new registration techniques are necessary for their detection. The south polar ice offers the unique opportunity to implement existing Cherenkov techniques as well as registration of radio and acoustic waves from the neutrino interaction. A simulation of a $\sim 120\,\mathrm{km}^3$ hybrid optical/radio/acoustic detector showed that event rates of ~ 10 per year can be achieved.
In this simulation the ultrasonic parameters of antarctic ice regarding absorption, scattering and environmental noise pose the key uncertainty. To evaluate the acoustic properties in-situ, the SOUTH POLE ACOUSTIC TEST SETUP (SPATS) has been created. An array of custom-made ultrasonic sensors and transmitters will be deployed on three strings in the upper 400 m of the holes of the ICECUBE experiment. The status of the experiment and a first evaluation of its performance are presented here.

1. Motivation

At energies above $4 \cdot 10^{19}\,\mathrm{eV}$, cosmic ray protons are assumed to be effectively absorbed in photo-pion production on the cosmic microwave background. The neutrinos generated from the subsequent decay of the charged pions can not only shed new light on this absorption mechanism, but also provide valuable insight on neutrino interactions at center-of-mass energies on the $10 - 100\,\mathrm{TeV}$ scale. Yet, due to the low predicted fluxes, future [1] and currently build [2, 3] Cherenkov neutrino telescopes will not be able to detect more than $\sim 1\,$event/year from this neutrino flux.

Therefore new detection methods for cosmic neutrinos in the EeV range are currently investigated. Both detection of radio and acoustic waves from the hadronic and electromagnetic cascades following a neutrino interaction in a dense medium, seem promising. In the absence of a calibration source of EeV particles a hybrid detector implementing more than one registration technique is a proximate idea to constrain possible systematic effects on a single method. For the glacial ice at South Pole, absorption lengths of $\sim 1\,\mathrm{km}$ have been measured for radio waves [4] and values of up to $10\,\mathrm{km}$ are predicted for sound waves [5]. Combined with ten times higher amplitudes from the thermo-acoustic mechanism and very low anticipated noise levels, despite

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its remoteness the antarctic ice seems very favourable for such a combined experiment.

To evaluate the potential of this approach, a simulation of a hybrid array of optical, radio and acoustic sensors has been performed [6, 7]. Radio and acoustic modules are assumed on 91 hexagonally arranged strings of 1.5 km depths with a 1 km spacing centered around the IceCube detector extended by 13 additional strings of optical detector modules. The effective neutrino volume for each detector component and for coincident detection is shown in figure 1. For a GZK neutrino flux from [8] with $\Omega_\Lambda = 0.7$, more than 10 events/year are found for both techniques with a significant overlap fraction that will allow for cross-calibration. Table 1 shows a summary of the obtained event rates.

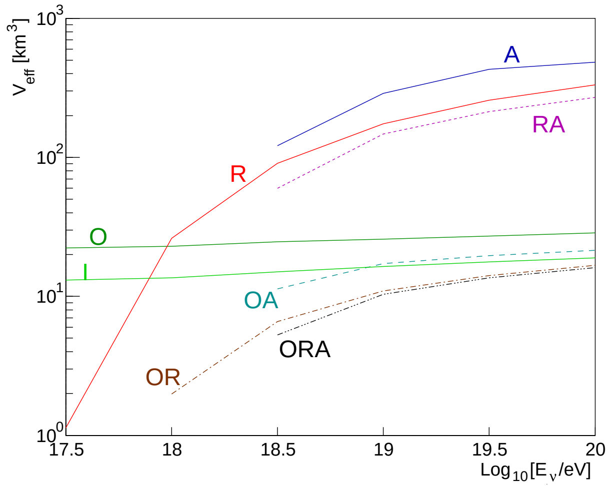

Figure 1. Effective neutrino volume versus energy for the different detection methods and their combinations: IceCube (I), optical (O), radio (R) and acoustic (A).

One of the key uncertainties in this simulation are the acoustic ice properties. Absorption lengths are extrapolated from lower frequencies and higher temperatures. Scattering and ambient noise levels are assumed to be negligible, with the sensor threshold given by the electronic self noise.

2. Setup

In order to verify these presumptions in an in-situ measurement, the South Pole Acoustic Test Setup has been created. Three main goals shall be addressed: measurement of the absorption length, the sound velocity profile and the ambient background noise. The system – which is depicted in figure 2 – consists of 21 acoustic stages on three strings in the depth range of 80 m to 400 m. Each stage contains a transmitter module above a sensor module plus two *spacer balls* ensuring a minimal distance of the modules from other installations. The three strings will be arranged in an irregular triangle with distances of 125 m and ∼ 400 m and will be deployed in the upper part of three holes drilled for the IceCube experiment. Suspended from a support rope, the stages are lowered into the holes after installation of the IceCube strings. Analog signals will be brought to the surface on electrical cables where they are digitized by a PC-based data-aquisition system in the *acoustic box*. Connected through previously unused wire pairs in the IceCube surface cables, the data from all three strings is then collected on a *Master-PC* in a central facility, from where they are sent to the northern hemisphere via a sattelite link. Installation of the system is planned for the polar season 2006/2007.

	A	R	O	I	RA	OA	OR	ORA
Event rate [yr^{-1}]	16.0	12.3	1.2	0.7	8.0	0.3	0.2	0.1

Table 1. Numer of cosmogenic neutrino events per year detected by the different methods and their combinations.

2.1. Acoustic stage

Both acoustic sensors and transmitters are based on piezoelectric ceramics. In each sensor module three channels consisting of a cylindrical PZT elements of 5 mm height and 10 mm diameter and a three stage amplifier circuit are arranged in a plane at angles of $120\,^\circ$ to each other. Good acoustic and mechanical coupling to the walls of the 12 cm diameter steel pressure housing is ensured by screws excerting force on the ceramics via the amplifier boards. All sensor modules have been calibrated relative to a reference hydrophone in a large water tank using a pulsed broadband signal and comparing fourier spectra in a time-selective method [9, 10]. Significant improvement in sensitivity and equivalent self noise level has been found compared to the reference hydrophone.

Transmitters are built from ring-shaped piezo-ceramics of 20 mm diameter that are cast in epoxy. High voltages pulses of $10\,\mu$s lenght at an adjustable amplitude of up to 1 kV are generated by an inductivity circuit that is discharged via the PZT element. The electronic board is housed

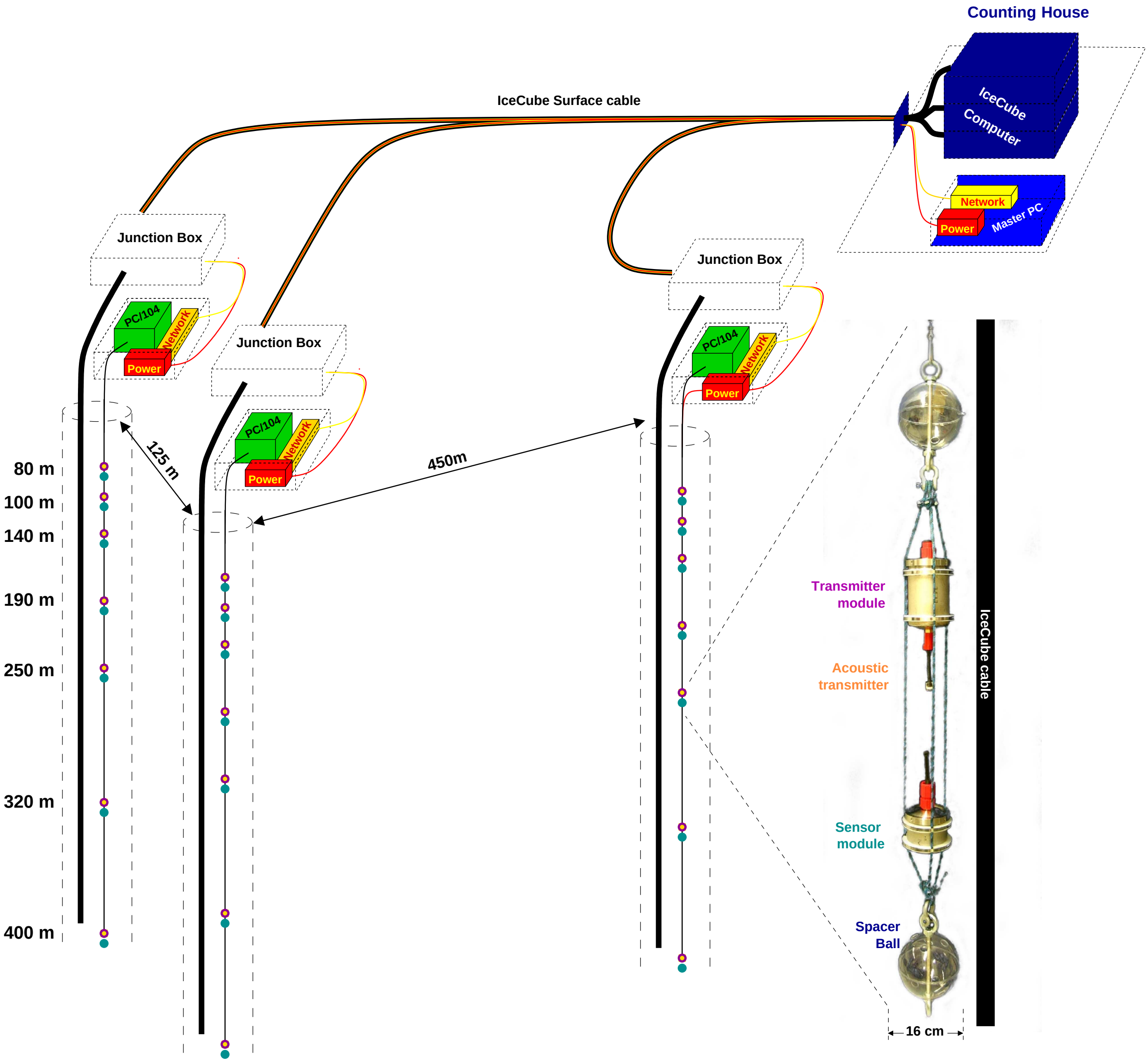

Figure 2. Schematic of the South Pole Acoustic Test Setup (left) and picture of an acoustic stage (right)

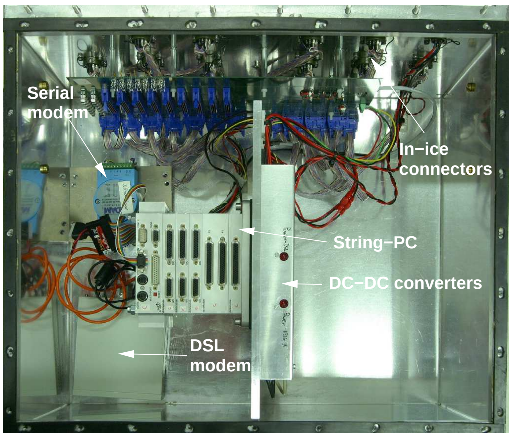

Figure 3. The *acoustic box* with the *String-PC*, DSL and serial modems

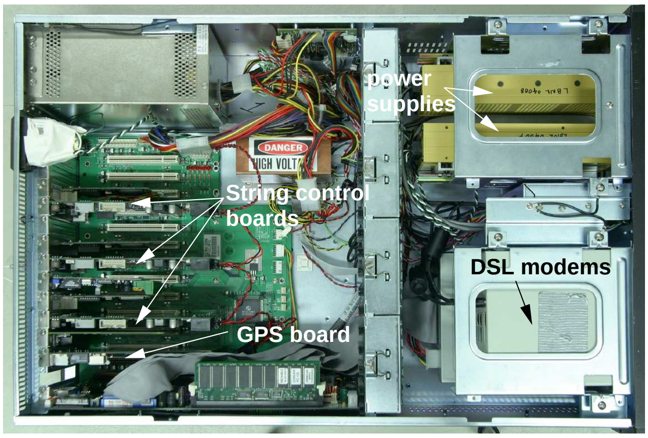

Figure 4. *Master-PC* with string control boards, DSL modems and GPS board

in a cylindrical steel container similar to the sensor module, while the active piezo-electric element is placed outside of the housing for best coupling to the surrounding medium. Each transmitter also houses a temperature sensors with a PT1000 element. At the lowest stage in each string these are replaced by pressure sensors to verify the installation depth. Azimuthal and overall variability of the transmitters has also been probed in a water setup, showing a deviation from isotropic emmission by no more than 40 %. Details of all the calibration efforts are presented in [11].

2.2. Data acquisiton

In the *acoustic box* shown in figure 3, all sensors and transmitters on one string are controlled by a *String-PC* based on the industrial PC/104 standard. Three commercial 12-bit ADC cards are used to aquire simultaneous data from all three channels in one module, with a sampling rate of 3×1.25 MHz that can be arbitrarily distributed among the seven stages in a string. Together with another slower ADC/DAC module of 500 kHz this system also controls transmitters as well as temperature and pressure readouts. Data acquisition is controlled by a 600 MHz CPU module with 512 Mb, that can also be used to e.g. apply low-level filter algorithms. The sensors and transmitters can be individually powered on and off, allowing for a rather low 35 W average power consumption per string. The DC voltage levels required for sensors, transmitters, the *String-PC* and other components in the *acoustic box* are generated by wide-range DC-DC converters from the 96 V that are provided through two pairs of electrical wires from the *Master-PC*. To communicate the data to the *Master-PC*, a symmetric DSL connection with a bandwidth of 2 Mbps is available on another wire pair. DSL devices have not been found rated better than down to $-20\,^{\circ}$C, but proper thermal mounting allows for quick heating of the devices and operation down to at least $-60\,^{\circ}$C. As a backup, another 32.8 kbps serial RS422 connection is provided to each *String-PC* on the last of four available wire pairs to the *Master-PC*.

From the *Master-PC* shown in figure 4, each *String-PC* is accessed and controlled via a custom-made PCI interface board, that also regulates current and voltage levels to one *acoustic box* and allows to switch between the different communication modes. In addition, in order to synchronize the three strings a GPS-based *IRIG-B* time coding signal is distributed from the *Master-PC* to the *String-PC*s via these boards on the same wire pair and alternating with the RS422 signal. The *Master-PC* is integrated in the South Pole network, which allows for remote control of the setup from and a modest amount of data to be transferred to the nothern hemisphere via a satellite link. With an estimated bandwidth of $\sim$ 50 kbps, about 1000 events/day will be available for online analysis. The bulk of the data, that can be recorded with up to 135 Mbps will be stored on magnetic tapes and transported north in the following austral summer season.

3. Testing and verification

Being the first ultra-sonic and outdoor computing installation at South Pole, the system has undergone most extensive testing. With an ambient temperature of $-50\,^{\circ}$C, all in-ice devices have been tested for functionality down to $-55\,^{\circ}$C. To meet the requirements from ambient and additional freeze-in pressures, water-tightness of the pressure housings up to 120 bar has been verified. The complete data acquisition system of one *acoustic box*, full-length in-ice cables and a complete stage has also been tested in a freezer for three months. Power-cycling the *String-PC* with off-times of up to 24 hrs while reaching temperatures down to $-60\,^{\circ}$C in the *acoustic box* did not result in any instability of the setup. Also for transmission of acoustic signals in air from the SPATS transmitters to the SPATS sensors, an increase of signal strength with decreasing temperature was found.

Further tests have been performed in a *dry* installation of the complete setup with all 21 stages in a big experimental hall, showing the full functionality of the complete setup. From a smaller setup in air with five stages, first estimates of the directional reconstruction capabilities from the three channels in a single stage could be obtained.

In a large scale water setup in a frozen lake in northern Sweden, these results could be further improved, along with showing the capabilities of the setup of sending signals over distances of up to 800 m. At the same time, estimates on azimuthal and polar variability of sensor and transmitter modules could be obtained. Outside operation of an *acoustic box* in the wet and cold conditions north of the polar circle gave further trust in the robustness of the design. Details of these test are given in [11].

4. Performance

The performance of the system with respect to the experimental aims has been investigated. The timing resolution was found to be in the order of 1 μs, corresponding to an uncertainty in the propagation velocity measurement well below the positioning error inside the IceCube holes. In order to study the performance on the absorption measurement, a small Monte Carlo study has been performed. The acoustic signal from a transmitter j at a sensor i in a distance d_{ij} is given by

$$A(j,i) = T_j S_i \frac{1}{d_{ij}} \exp\left(-\alpha d_{ij}\right) , \quad (1)$$

where T_j denotes the acoustic emission amplitude of the transmitter and S_i is the unknown sensitivity. The absorbtivity α can then be determined from the ratio of two measured amplitudes $^{A(j,i)}\!/_{A(k,i)}$ from different transmitters j and k at the same

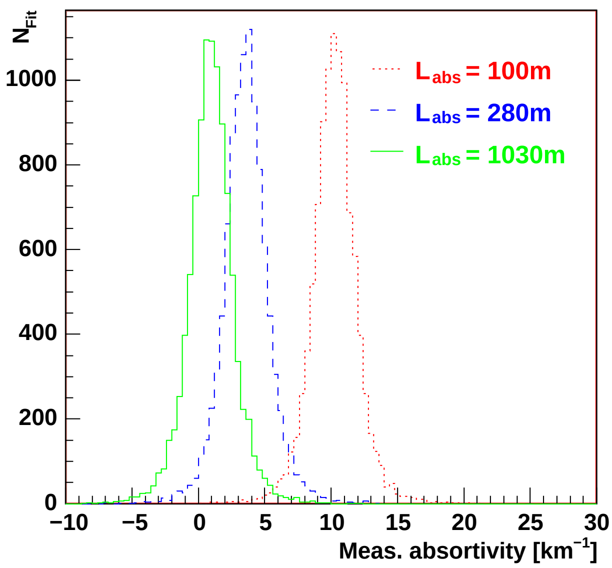

Figure 5. Probability to measure an absorptivity values for a given input absorbtivity.

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sensor i, that is in first approximation independent of S_i. Three such ratios can be build with the three stages at each depth layer. Yet due to the variation of sensitivity with azimuthal angle φ, $S_i(\varphi)$ will not exactly cancel out in the above ratio. Since azimuthal orientation of the SPATS sensors can not be controlled during deployment, the observed 40% variation is taken as an uncertainty. From the simulation, the resulting probability distribution to measure a certain absorptivity value for some assumed input absorptivity is shown in figure 5. The width of the distribution, i.e. the uncertainty on the absorbtivity is independent of the absorptivity value, from which a 50% chance to derive a lower limit of $L_{abs} > 1200\,\mathrm{m}$ on the absorption length can be found. The method can been further refined using all possible sensor/transmitter combinations and assuming a common absorption length at all depth.

5. Conclusion

Developement of acoustic detection techniques for ultra-high energy neutrinos in the glacial ice at South Pole seems a rewarding enterprise. From the simulation of the hybrid optical/radio/acoustic array GZK event rates of more than $10\,\mathrm{yr}^{-1}$ have been found, with a significant overlap fraction in the acoustic and radio methods that will allow for cross-calibration. To address the key uncertainties in the simulation the South Pole Acoustic Test Setup has been created to measure in-situ the absorption length, propagation velocity and noise levels for ultra-sonic signals at South Pole. The complete system and all its components have been calibrated in water setups and thoroughly tested in cold conditions. With the data of the setup that will be installed in austral summer 2006/2007 a much more detailed evaluation of the potential of a hybrid array may be obtained. Based on this, a design proposal for a large scale EeV neutrino telescope may be developed.

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