Speed of sound in bubble-free ice

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The speed of sound in a large volume of bubble-free ice was measured with high accuracy using a linear array of six piezoceramic lead zirconium titanate (PZT) receivers. This array was deployed in an ∼3 m³ water tank, which was cooled down to −20 °C. The freezing process was performed inside a cooling container. Bubble-free ice was obtained using a freeze control unit, which filters and degases the water during the freezing process. A dedicated geometry was used to position PZT receivers and an emitter such that systematic errors were minimized. With this setup the longitudinal and the transverse components of the speed of sound were measured at temperatures between 17 and 0 °C in water and between 0 and −20 °C in ice with an uncertainty of ∼0.3%.

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I. INTRODUCTION

Within the R&D program of the acoustic detection of ultrahigh energy neutrino interactions in the deep glacial ice at the South Pole, a good understanding of the acoustic properties of ice is essential. For this aim the Aachen Acoustics Laboratory (AAL) has been installed and commissioned in 2007. It provides an infrastructure and a test facility for the development and tests of new methods for the acoustic neutrino detection, in particular, detector development and ice properties. The first result, the speed of sound in bubble-free ice measured with high precision, is reported here.

II. EXPERIMENTAL SETUP

A linear array of six receivers and one transmitter was built and deployed inside a large water tank (1.85 m diameter and 1 m depth). Due to this large size, the speed of sound can be measured with a time-of-flight setup without being affected by distortions from reflections at the surfaces. The water tank has been developed for the IceTop airshower detector at the South Pole. Its frozen ice is used as an optical Cherenkov detector. Perfectly clear ice without air bubbles and cracks throughout the whole volume is produced by a freeze control unit (FCU), which was developed at the University of Delaware.

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A. The acoustic array

One transmitter and six identical acoustical receivers labeled S1–S6 (2 mm thick and 5 mm radius) were accurately positioned to form a linear array. The setup is illustrated in Fig. 1. The relative position of the transducers (receivers and transmitter) provides an equal propagation path length (dₕ=20 cm) between each two adjacent receivers of the array. The faces of the receivers are placed perpendicular to the expected direction of the acoustic wave. No preamplification was used. For the precise positioning of the transducers weights of 5 kg were attached to them. Above each receiver a temperature sensor of type DS28B20 (Dallas Semiconductors) was placed to monitor the local temperature. The absolute calibration of the sensor has an uncertainty of 0.5 °C and corresponds to a constant offset in the temperature dependent measurement of the speed of sound.

Piezoceramic Lead Zirconium Titanate (PZT) disks of type PRYY+0372 (PI Ceramics) were used as acoustical receivers. They were sealed in a resin of epoxy to make them waterproof. The epoxy layer was cut to a thickness of 3.5 mm to permit a high transmission rate of the sound wave. A PZT tube (2 cm high, 7 mm inner diameter, and 1 cm outer diameter) labeled E1 was used as a transmitter.

B. Cooling and ice production

The central element of the setup is an IceTop tank with a FCU embedded in a cooling container. The tank and the FCU were developed within the IceCube project for the surface detector IceTop with the purpose to detect air showers induced by cosmic rays. The inside of the container is supplied with cold air (down to a minimum of −25 °C) via a cooling plant provided with a regulation of the temperature. In this setup the freezing is mainly caused by the heat transfer of air convection. The sides of the tank are isolated and the ice layer inside the tank starts to grow progressively from the top (water surface) to the bottom. During the cooling process, the FCU runs permanently to degas the water via a circulation pump with a semipermeable membrane and a vacuum system. In addition to the degassing, the FCU removes the excess water resulting from density difference between water and ice to avoid cracks caused by overpressure. By using this method the produced ice is completely crack/bubble-free. Visual inspections of the ice confirm the high quality of the frozen ice. No imperfections such as bubbles or cracks are visible within the entire volume. Three sets of temperature sensors monitored the temperature at different locations. The first set measured the air temperature inside the container, the second set measured the water/ice tempera-

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The speed of sound can be calculated as

\[ v_{\text{sound}} = \frac{d_0}{\langle \Delta t_{ij} \rangle} \]  

(1)

where \( d_0 \) is the propagation path length and \( \langle \Delta t_{ij} \rangle \) is the mean value of the time delay between two adjacent receivers.

### IV. RESULTS

#### A. Measurements in water

As a proof of principle the speed of sound was determined at different temperatures in water. Figure 3 shows the agreement between the measured values (points) and the third order polynomial describing the literature values. The good agreement proves the validity of the method. Systematic errors, given by the position of the transducers and their size, are included in the plot. The agreement of the measured values with literature is better than the assumed systematic errors indicate.

#### B. Measurements in ice

1. **Longitudinal component**

Using a similar approach as in water, the speed of sound was determined in ice at different temperatures in the range between 0 and \(-20 \, ^\circ\text{C}\). Figure 4 shows a linear behavior of the measured longitudinal speed of sound \( v_{\text{sound}}(T) \) versus temperature \( T \). From a linear fit the slope, which expresses the temperature coefficient, is extracted. It is compared to literature values in Sec. V. The slope is

\[ \frac{dv_{\text{sound}}(T)}{dT} = -2.812(\pm 0.012) \, \text{m/(s} \, ^\circ\text{C)} \]  

(2)

and the offset at \( 0 \, ^\circ\text{C} \) is

\[ v_{\text{sound}}(T = 0 ^\circ\text{C}) = 3837.9(\pm 5.3) \, \text{m/s}. \]  

(3)

The slope has been determined with statistical errors only as systematic errors are suspected to affect the temperature dependence insignificantly. The error in the offset includes statistical and systematic errors. Since the horizontal temperature field is homogeneous, the uncertainty in the path length due to diffraction is much smaller than the uncertainty related to the positions of the sensors.

2. **Transverse component**

Ice, as a solid medium, allows in addition to pressure waves the propagation of shear waves. The corresponding transverse component of the speed of sound is expected to be smaller than the longitudinal component. In our setup, the challenging part was to separate the signal of the shear wave from different reflections of the pressure wave off the walls. The arrival time of all possible reflections was calculated and identified in the recorded signal. These calculations were possible by taking into account the geometry of the ice block, the position of the PZT transducers, and the longitudinal speed of sound. For receivers S3–S6 the reflections arrived earlier than the shear wave [see Fig. 2(b)]. For receiver S1, the separation between the decaying signal from the pressure wave front and the signal from the shear wave
was not possible. Thus, the signal of the shear wave was identified by receiver S2 in a temperature range between −20 and −13 °C. Here the border between ice and water is sufficiently deep below the receivers. The position of this border changes during the cooling process.

Figure 5 shows the transverse speed of sound versus temperature. From a linear fit the slope is extracted. Because only one receiver was able to identify the signal, the measurement here depends on the starting time of the emitted and received signals. Thus, the uncertainties are larger than before. The resulting slope is

\[ \frac{dv_{\text{sound}}(T)}{dT} = -1.435(\pm 0.028) \text{ m/(s °C)}. \] (4)

The offset at 0° is

\[ v_{\text{sound}}(T = 0 \text{ °C}) = 1826(\pm 47) \text{ m/s}. \] (5)

V. COMPARISON WITH LITERATURE

A. Longitudinal component

Table I shows the measured temperature coefficients of the longitudinal component of the speed of sound. These
The values is done using statistical errors only. The error bars are the sum of statistical and systematic errors. The line fit to

FIG. 3. (Color online) Speed of sound in water. The error bars are the sum of statistical and systematic errors (see text).

FIG. 4. (Color online) Speed of sound for pressure waves in bubble-free ice. The error bars are the sum of statistical and systematic errors. The line fit to the values is done using statistical errors only.

FIG. 5. (Color online) Speed of sound for shear waves in bubble-free ice. The error bars are the sum of statistical and systematic errors. The line fit to the values is done using statistical errors only.

TABLE I. Comparison between temperature coefficients of the speed of sound of pressure waves for laboratory measurements and in situ measurements in Antarctica and Greenland.

<table>
<thead>
<tr>
<th>$d v / d T$</th>
<th>Author</th>
</tr>
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<tbody>
<tr>
<td>$-18$</td>
<td>Joset and Holtzscherebr</td>
</tr>
<tr>
<td>$-7.4$</td>
<td>Thiel and Ostensoh</td>
</tr>
<tr>
<td>$-5.5$</td>
<td>Brockamp and Kohnenl</td>
</tr>
<tr>
<td>$-4.5$</td>
<td>Thyssenf</td>
</tr>
<tr>
<td>$-2.30 \pm 0.17$</td>
<td>Kohnenf</td>
</tr>
</tbody>
</table>

Laboratory

| $-2.3$    | Robinf |
| $-3.4$    | Bass et al.h |
| $-2.2$    | Brockamp and Querfurthab |
| $-2.81 \pm 0.01$ | AAL |

values are separated into laboratory and in situ experiments in Greenland and Antarctica. The listed temperature coefficients differ strongly. The temperature coefficient determined in this paper using the AAL setup is consistent with the range of previous measurements listed in the table.

Figure 6 shows in situ measurements in a temperature range of $-16$ to $-58$ °C as unfilled dots and a fit to all of these data done by Kohnen. In this figure a clear difference compared to the values obtained by the AAL setup is visible. We suspect these differences to be related to differences in the elastic properties of the considered ice. The ice of the...
measurements obtained and the corresponding reflections. Differences to previous
sured by separating the signal from that of pressure waves
of high quality, agrees with the error band of the AAL mea-
measurement was tested in water and compared with literature
positioned PZT disks and calculating time differences be-
measurements in ice in
in Antarctica and Greenland.

\[
\frac{dv_{\text{sound}}}{dTm} (\text{s}^\circ \text{C}) \quad \text{Author}
\]

<table>
<thead>
<tr>
<th>In situ</th>
<th>Laboratory</th>
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<tbody>
<tr>
<td>−3.4</td>
<td>Brockamp and Ostenso(^a)</td>
</tr>
<tr>
<td>−3.6</td>
<td>Brockamp and Kohnen(^b)</td>
</tr>
<tr>
<td>−1.20 ± 0.58</td>
<td>Kohnen(^c)</td>
</tr>
<tr>
<td>−1.4</td>
<td>Bass et al.(^d)</td>
</tr>
<tr>
<td>−1.1</td>
<td>Brockamp and Querfurth(^e)</td>
</tr>
<tr>
<td>−1.43 ± 0.03</td>
<td>AAL</td>
</tr>
</tbody>
</table>

Reference 20.
Reference 25.
Reference 7.
Reference 21.
Reference 22.

The measurement of the speed of sound in bubble-free
ice was performed by building a setup using very accurate
positioned PZT disks and calculating time differences be-
tween two received signals. The ice was degassed during
freezing and clear bubble-free ice was obtained. The mea-
urement was tested in water and compared with literature
yielding a good agreement. The speed of sound for pressure
waves at different temperatures was determined with an ac-
curacy of 〜0.3\%. For shear waves a value could be mea-
sured by separating the signal from that of pressure waves
and the corresponding reflections. Differences to previous
measurements obtained in situ in Greenland and Antarctica
appear and are assumed to be related to the quality of the
considered ice. Our result is consistent with the result of
Bennet.\(^8\)

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