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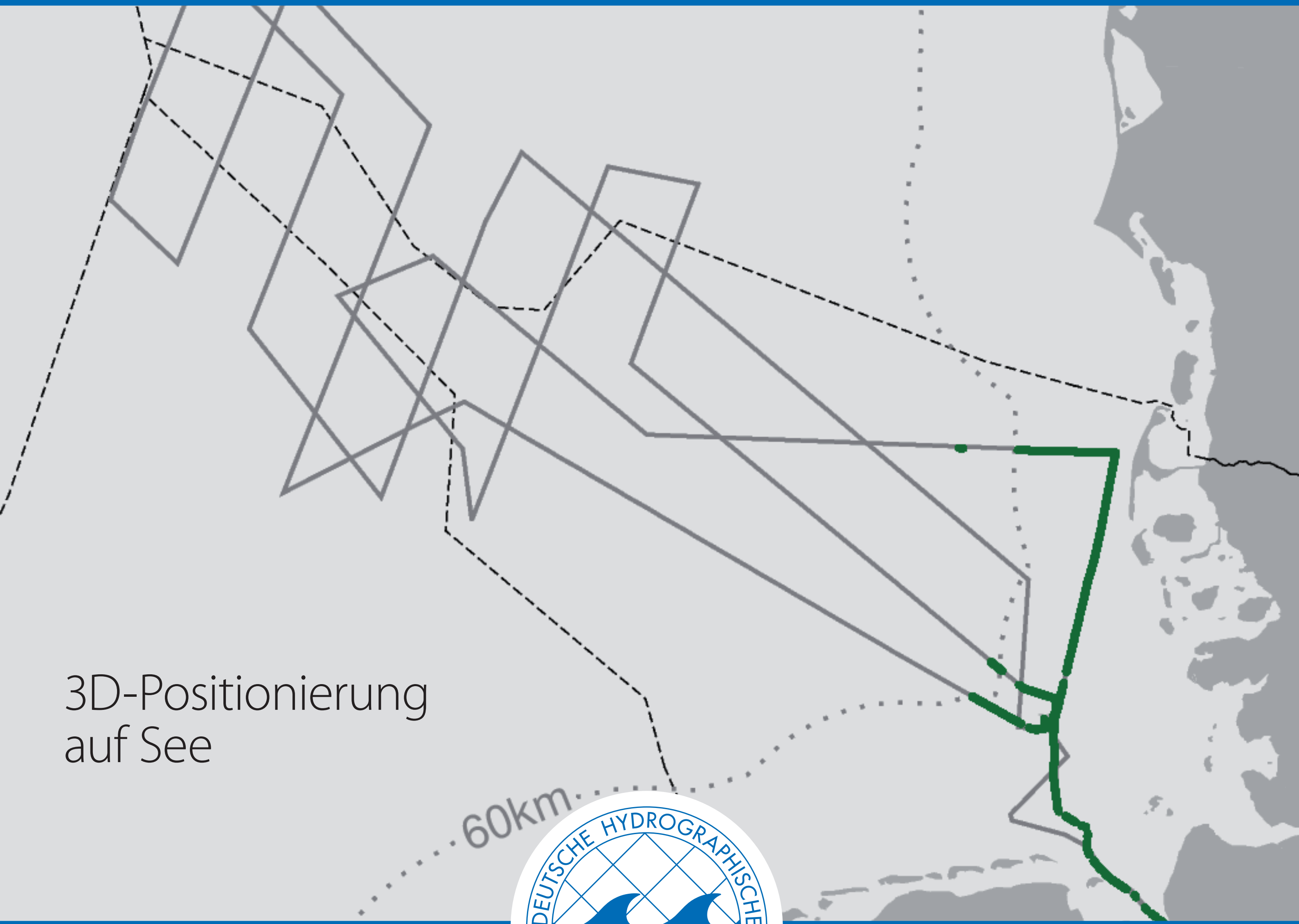

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Measuring sea ice thickness

Exploring the feasibility of echo sounders for close-range determination of sea ice draft

An article by ELLEN WERNER

This work explores the potential of using commercial single-beam echo sounders for accurate thickness determination of sea ice. Therefore, an own sensor system has been developed which allows to study the performance of different echo sounders monitoring sea ice under varying environmental conditions in a laboratory setup. The sensor system consists of three single-beam echo sounders operating at different frequencies (115 kHz, 200 kHz, 500 kHz), a CTD probe measuring physical water properties and instruments frozen in the ice measuring temperature and salinity. Different experiments were conducted observing the sea ice state while performing acoustic range determinations. Subsequent, statistical measures were calculated to evaluate the accuracy of inferred sea ice draft. The study concludes that a draft accuracy of ±0.5 cm is reached by the implemented method under specific conditions and that the acoustic approach for determining sea ice draft thickness is applicable using frequencies of 115 kHz or 200 kHz.

sea ice draft | SBES | ULS – upward looking sonar | acoustic properties | accuracy evaluation
Meereistiefe | SBES | ULS – upward looking sonar | akustische Eigenschaften | Genauigkeitsabschätzung

In dieser Arbeit wird das Potenzial des Einsatzes kommerzieller Einstrahlecholote zur genauen Bestimmung der Meereisdicke untersucht. Dazu wurde ein eigenes Sensorsystem entwickelt, mit dem die Performance verschiedener Echolote zur Überwachung des Meereises unter verschiedenen Umweltbedingungen in einem Laboraufbau analysiert werden kann. Das Sensorsystem besteht aus drei Einstrahlecholoten, die mit unterschiedlichen Frequenzen arbeiten (115 kHz, 200 kHz, 500 kHz), einer CTD-Sonde zur Messung der physikalischen Wassereigenschaften und mehreren im Eis eingefrorenen Instrumenten zur Messung von Temperatur und Salzgehalt. Es wurden unterschiedlich angelegte Experimente durchgeführt, bei welchen der Meereiszustand beobachtet und gleichzeitig akustische Entfernungsbestimmungen vorgenommen wurden. Anschließend wurden statistische Maße berechnet, um die Genauigkeit der abgeleiteten Meereistiefe zu bewerten. Die Studie kommt zu dem Schluss, dass mit der implementierten Methode unter bestimmten Bedingungen eine Tiefgangsgenauigkeit von ±0,5 cm erreicht wird und dass der akustische Ansatz zur Bestimmung der Meereis-Tiefgangsdicke bei Frequenzen von 115 kHz oder 200 kHz anwendbar ist.

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Motivation

Sea ice plays an important role in today's climate studies. The sea ice covering the polar oceans is a critical component of the global climate system serving as a climate change indicator as well as an amplifier of the same (Golden et al. 2020). Accurate measurement of sea ice thickness is thus critical to better understand, model and predict climate change. However, determining the sea ice thickness remains challenging as no fully adequate method to measure ice thickness distribution and its variability with appropriate resolution in space and time exists (Wadhams and Amanatidis 2006). Several techniques in use involve either in-situ measurements by drilling a hole through the ice or by deploying instruments in or on the ice. Other currently used methods are calculating the ice thickness from indirect measurements. Direct remote monitoring of sea ice change, however, is difficult and under scientific investigation. Using acoustic sensors may provide a possible approach to measure the total sea ice thickness (Bassett et al. 2020).

So far, there have been numerous attempts and techniques with acoustic sensors in use, e.g. mounted at stationary buoys and moorings or moving underwater platforms. However, there have been only sparse investigations on accuracy measures of using present days sonar technologies. Although sea ice thickness is next to its extent a fundamental state parameter for sea ice-related studies and also crucial for almost all sea ice-related investigations performed in a laboratory, there have only been few attempts in remotely monitoring sea ice change in a close-range environment. This is where the studies presented in this article want to step in.

The underlying Master Thesis analyses and discusses the use of commercial echo sounders, mounted as upward looking sonars (ULS), in a combined sensor setup for determining the thickness of laboratory-grown sea ice and provides corresponding error assessment. Within that scope, three main research questions are experimentally investigated: Which acoustic frequency is optimal for a given application? How accurate is sea ice draft determination from echo sounders compared to conventional techniques? Which impact has the sea ice condition (varying temperature and salinity) on acoustic range measurements?

Background

Sea ice forms from ocean water, and hence the presence of salt dictates its physical processes. This makes sea ice a morphological complex media changing its physical properties and structure during ice growth and decay. Temperature and salinity of sea ice are the prime controlling variables determining the sea ice state. Any temperature change directly affects the sea ice porosity and thus its acoustic reflectivity (Petrich and Eicken 2010). Direct measurement of both, temperature and salinity, are difficult and accurate in-situ measurements require the inserting of corresponding devices into the ice.

A good overview of ice internal structures and the complexity of sea ice in relation to acoustic properties is provided by Bassett et al. (2020). Of special interest for the presented study is the complex region at the transition zone from sea ice to sea water, which is commonly referred as skeletal layer. It displays a smooth transition from properties of sea water to the bulk properties of sea ice instead of a clearly determinable surface. Especially for acoustic wavelengths in the scale of the skeletal layer thickness, the sea ice underside, which forms a lamellar structure (as can be seen in Fig. 1), has to be determined as a rough surface. And at a rough surface in comparison to wavelength, the physical structure becomes controlling and acoustic scattering is less coherent (Bassett et al. 2016; Stanton et al. 1986).

Sea ice is less dense than the sea water it is floating on. The assumption that the ice sheet is in hydrostatic balance, leads to the determination of two layers with respect to the water level: ice freeboard h_{free} (height of the ice above the water-line) and the ice draft h_{draft} (height of the ice below the water-line). Adding both layers results in the total ice thickness h_{ice}.

The distance measured by the echo sounder

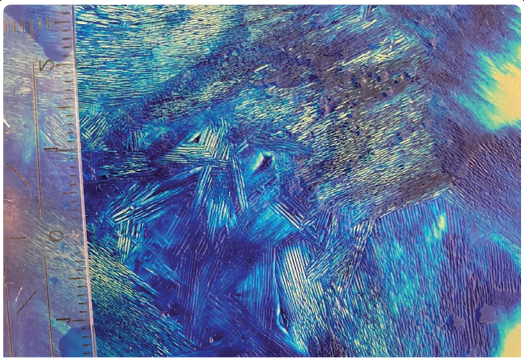

Fig. 1: The complex microstructure of the skeletal layer, its size and orientation can be seen by pouring colorant on the bottom of ice cores

is the range t_{w-i} from the transducer face to the water-ice interface. A schematic representation of sea ice vertical components and distances according to the laboratory conditions is shown in Fig. 2. As the ice draft constitutes about 90 % of the ice thickness, it represents a robust proxy for the total ice thickness while observing its change.

Methods

The Max Planck Institute of Meteorology and the Sea Ice Research Group of the Institute for Oceanography, Universität Hamburg, operate a sea ice laboratory with water tanks in a freezing chamber where artificial sea ice can be grown. The air temperature in the freezing chamber can be set to temperatures down to –22 °C. The large water tank, which has been used for the main experiments, is 194 cm long, 66 cm wide and filled with water up to a height of ~90 cm at the beginning of experiments (cf. Fig. 3).

A new sensor setup is developed and data acquisition routines for all used instruments are programmed. The time triggered acquisition routine for the echo sounders is publicly avail-

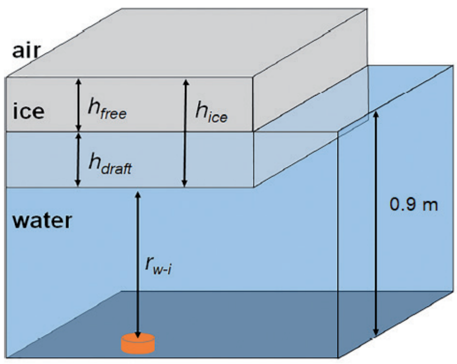

Fig. 2: Schematic representation of sea ice vertical components showing the relations between the total ice thickness, freeboard and draft. The depth label is specific to the tank measurements of the experimental setup. Adopted from Bassett et al. (2020)

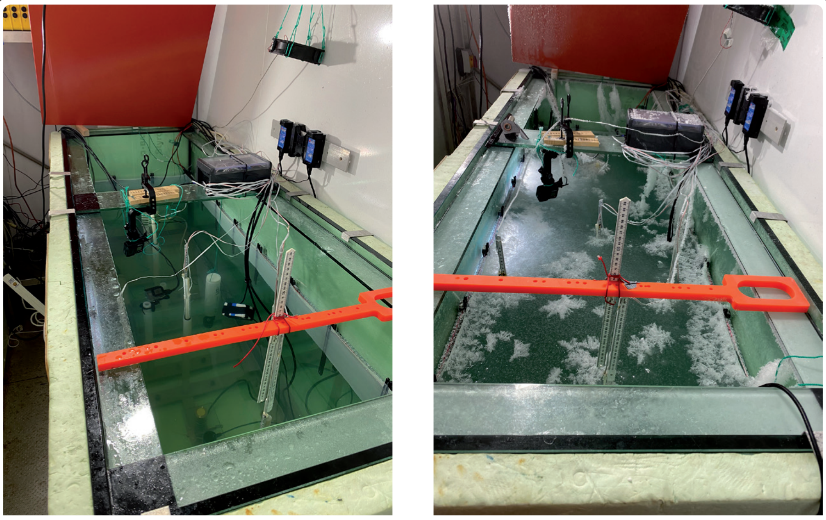

Fig. 3: Large tank in the freezing chamber insulated at bottom and sidewalls with 5 cm thick Styrofoam plates to ensure the water inside the tank is only cooled through the air-water interface as under natural conditions. (a) without sea ice (b) with sea ice

able on Github (https://github.com/elwerner/SeaIceSonar). Data acquisition and analysis is done using Python programmes. After initial testing, a successful barcheck has been conducted. Within four main experiments (each lasting around one week, including an initial freezing period, a melting period to warm the sea ice, another freezing period and a final ice decay period) acoustic range measurements of three echo sounders with different frequencies and resolutions have been recorded. In addition to the acoustic monitoring, physical parameters of the growing sea ice were observed to conclude on acoustic reflection behaviour. The experiments have been tailored with varying salinity of the initial tank water. Retrieved draft measurements of laboratory-grown sea ice up to 18 cm thick were compared and validated with reference measurements using rulers frozen into the ice sheet. Subsequently, it was analysed whether the inferred sea ice draft can reach an accuracy better than ±0.5 cm.

Sensor	Frequency	Beamwidth	Min. Range	Resolution
Airmar EchoRange	200 kHz	9°	0.4 m	18.75 mm
Tritech PA500	500 kHz	6°	0.1 m	1 mm
BlueRobotics Ping	125 kHz	30°	0.5 m	4 mm

Table 1: Extract of sensor specifications of the three used echo sounders

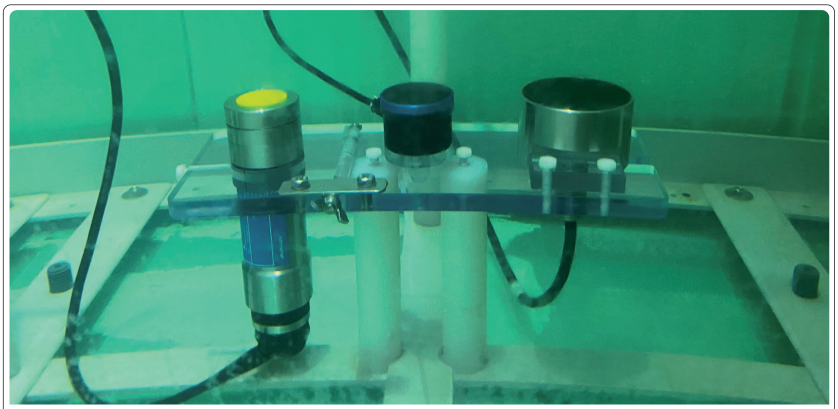

Fig. 4: From left to right: Tritech PA500, BlueRobotics Ping, Airmar EchoRange

The instrumentation used for the experiments includes three commercial echo sounders with different technical specifications which are listed in Table 1. The three single-beam echo sounders (SBES) used in the constructed mounting in the large tank are displayed in Fig. 4.

Furthermore, the instrumentation consists of auxiliary sensors including two CTD probes for measuring water column properties (for sound speed correction of the SBES data), seven T-Sticks (temperature sensor arrays frozen vertically in the ice to retrieve temperature profiles), a salinity harp (a sensor based on conductivity measurements to retrieve bulk salinity and liquid fraction of sea ice to state the sea ice permeability) and two GoPro cameras (to visually observe the sea ice state from outside the freezing chamber).

The recorded acoustic range measurements are in a first calculation step sound speed corrected and subsequently the sea ice draft gets determined by subtracting the distance between sonar head and the ice underside from the distance to the water surface. Additionally, a rolling median filter over ten measurements per sonar is computed to low pass filter the data. To compare the draft measurements inferred from the echo sounder data to the reference drafts read from rulers, residuals are calculated.

Experimental results

Implementation of the sensor system for echo sounder data acquisition in the sea ice laboratory is working as intended for acquiring temporal triggered echo sounder data. An impression of the resultant time series plot of the determined sea ice draft from all three echo sounders during the first experiment in the large tank is presented in Fig. 5.

Interpreting the visualised data, it can be summarised that the growth and decay of sea ice draft is detected by all three echo sounders over the full duration of the experiment. However, all sonars produce outliers and erroneous range recordings. The Tritech shows the least coherent but best trend approximating result. The Ping reveals major problems with its detection algorithm during the freezing periods detecting ranges far beyond the ice surfaces. The Airmar shows the most stable time series with outliers to the short range side, however, the instrumental vertical resolution results in a limited draft resolution showing a step wise behaviour.

Apart from these key results, four critical points become most obvious: reference measurements underestimating actual draft extent; more coher-

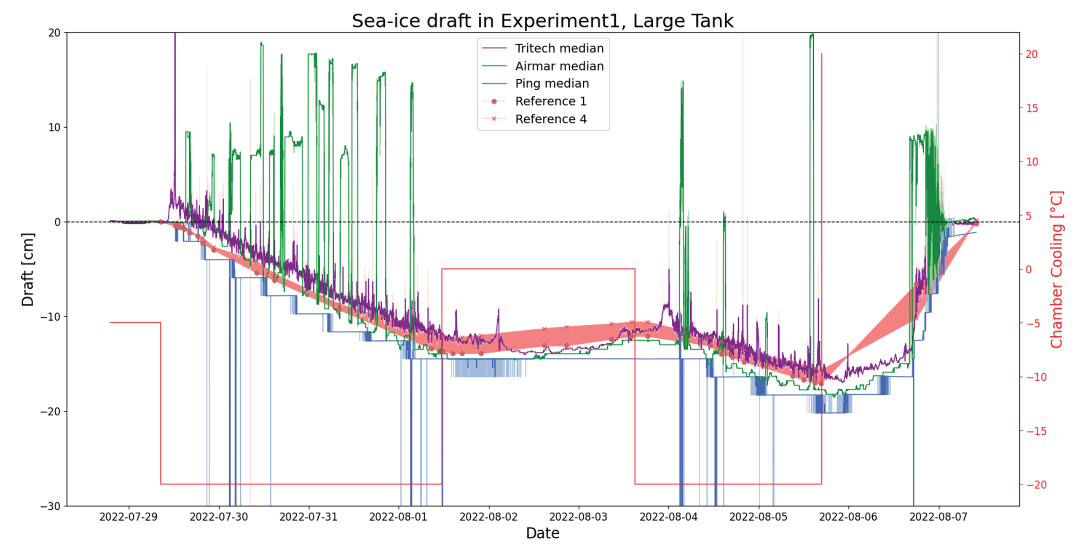

Fig. 5: Overview of sea ice draft measurements in experiment 1 in the large tank parallel plotted to the chamber cooling temperature (red). The black dashed line is indicating the water level. Ice drafts are plotted on the negative axis to represent ice growth downwards into the water column. The sonar data displayed is the calculated rolling median in bright colours (Tritech: violet; Airmar: blue; Ping: green) and the unfiltered raw data in pasty colours. The reference ice draft is supposed to lay in the rose coloured area between reference ruler readings from reference ruler 1 and 4

ent ice detection during the warm period; outliers and erroneous detections of all three echo sounders especially during ice growth; and Tritech discrepancy during initial ice formation and remaining offset when measuring on sea ice. The following second main experiment, conducted under similar conditions, proofed reproducibility of the measured phenomena and third experiment, conducted with a lower initial salinity, shows similar behaviour of the echo sounder data as observed before but making some effects even clearer.

To further investigate the Tritechs unintuitive behaviour at the beginning of ice growth and the remaining offset of 2 cm, a fourth side experiment in the large tank has been conducted. The recorded data confirms that the Tritech discrepancies of measuring too long distances only occur when measuring on saline sea ice.

Accuracy evaluation

Comparing the calculated root mean square error (RMSE) values of all echo sounder measurements during the different experiment periods, it becomes obvious, that the physical state of sea ice has a dominant impact on acoustic reflectivity and instruments precision. Generally, all instruments show more coherent ice detection during warm periods according to the RMSE values presented in Table 2. These conclusions fit to previously reported findings on sea ice reflectivity studies from Jezek et al. (1990) and Stanton et al. (1986).

The sea ice draft comparison to the reference measurements obtained from ruler readings delivered accuracy measures for all echo sounders.

Sensor	Freezing periods	Warm periods
Airmar EchoRange	±2.5 cm to ±5.7 cm	±0.2 cm to ±0.3 cm
Tritech PA500	±1.1 cm to ±7.7 cm	±0.3 cm to ±0.8 cm
BlueRobotics Ping	±2.4 cm to ±11.2 cm	±0.3 cm to ±0.4 cm

Table 2: RMSE values of instruments during different experiment periods

An example of a draft comparison between the Tritech data and reference readings during the third main experiment is given in Fig. 6. The 2 cm offset becomes clearly visible and calculated residual values confirm the offset. The calculated re-

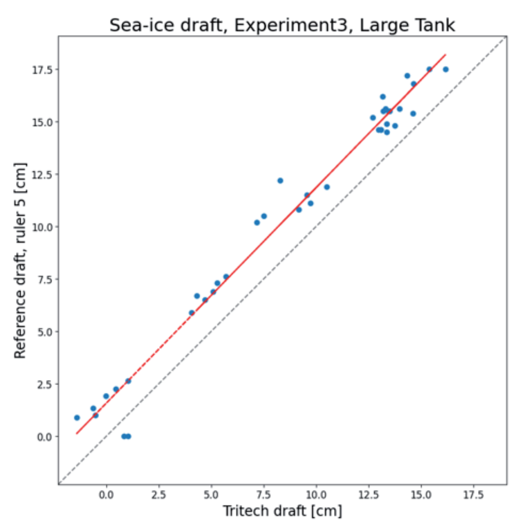

Fig. 6: Scatter plot for comparison of Tritech draft vs. reference draft. Experiment 3, large tank. Red line indicates the calculated linear trend line, grey line the line of zero residuals

Sensor	Residuals measuring on ice	Sensor resolution
Airmar EchoRange	−0.5 cm to +1.9 cm	1.9 cm
Tritech PA500	−1.6 cm to +1.9 cm	0.1 cm
BlueRobotics Ping	−0.3 cm to +1.0 cm	0.4 cm

Table 3: Range of residuals per sensor as accuracy measure in comparison to the sensor's individual resolution

siduals for all three sonars are displayed in Table 3. The Airmar EchoRange is measuring the sea ice underside with an accuracy in the range of its own instrumental resolution. The Ping Sonar also delivers accuracy values close to its resolution as long as the obvious erroneous detections are excluded. After subtraction of the constant offset of 2 cm when measuring on sea ice, the Tritech PA500 data set delivers an accuracy up to twenty times of the instruments stated resolution during freezing periods, however, improved accuracy is observed during periods of warm ice.

Apart from this sensor individual accuracy evaluations another general finding can be stated from the residuals: as the residuals are mainly positive, the echo sounder measurements generally underestimate draft extent observed by reference readings. Conclusively, the acoustic waves are not reflected at visually observed ice underside but penetrate into the ice in range of the skeletal layer thickness.

Conclusion

The idea of this work, using commercial echo sounders – originally designed for water depth measurements – for close-range determination of sea ice thickness, can be confirmed to be appropriated. A draft accuracy of ±0.5 cm is reached by the implemented method under specific conditions. The accuracy of inferred sea ice draft is shown to be strongly dependent on frequency, as acoustic scattering from the sea ice underside becomes less coherent the higher the operational frequency of the sonar is. The sonars with lower frequency show more coherent reflections from sea ice determining the ice draft with higher accuracy in scale of the instrument's vertical resolution. A strong relation between the acoustic reflectivity of the sea ice underside and the physical condition of sea ice is determined. Warm, porous sea ice is identified being a more resilient reflector for acoustic range detection than sea ice in the freezing process. By further analysing the signal return strength improvements of the sea ice underside detection are expected. Furthermore, this study shows that echo sounders acoustic waves penetrate into the water-ice transition layer in range of the skeletal layer thickness before being reflected. The presented work concludes that the acoustic approach for determining sea ice draft thickness is applicable using frequencies of 115 kHz or 200 kHz. //

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