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Measurement of the volume-backscattering spectrum from an aggregation of Antarctic krill and inference of their length-frequency distribution

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A B S T R A C T

Antarctic krill, *Euphausia superba*, were observed using a broadband echosounder and their length-density distribution was inferred from the echo data through a least square inversion. The observation was conducted in the Indian Ocean sector of the Southern Ocean in January 2014. The transmit signal was a 10-ms linear frequency-modulated signal with a frequency sweep of 20–200 kHz. A large aggregation of Antarctic krill was observed at a sampling station over the continental shelf. The volume-backscattering strengths in the frequency range of 85–187 kHz were determined from the observed echoes. In addition, the signal-to-noise ratio at each frequency was estimated and the measured volume-backscattering strengths were evaluated before inversion for accurate inferences. In this inversion, Antarctic krill were modeled as prolate spheroids and the target strengths were predicted by the distorted-wave Born approximation. The acoustically inferred mean length was in good agreement with the mode length determined by a net sampling performed immediately after the echo sampling. Also, the acoustically inferred length-frequency distribution was in reasonable agreement with the determined one from the net samples.

1. Introduction

Antarctic krill, *Euphausia superba*, is important to the Southern Ocean ecosystem (Everson, 2000) and a valuable fisheries resource. Krill are food for a number of species such as whales, seals, fishes, and penguins and other seabirds. The annual catch was 293,815 tonnes in the Austral summer of 2013/2014 and most of this was caught in the Scotia Sea near the Antarctic Peninsula (CCAMLR, 2015). To obtain information needed to protect the ecosystem and manage the krill fishery, acoustic and net surveys are conducted there periodically (Hewitt et al., 2004; Reiss et al., 2008; Fielding et al., 2014). Although there is less krill fishing in the Indian Ocean sector of the Southern Ocean, acoustic and net surveys are also conducted there to understand better its critical role in that ecosystem (Pauly et al., 2000; Nicol et al., 2008; Jarvis et al., 2010; Amakasu et al., 2011).

Although acoustic sampling generally requires less cost, time, and effort per unit survey area, and echo data typically have higher temporal and spatial resolutions than net samples, the interpretation of the echo data requires biological information (e.g. size, numerical density, and species) characterizing the echo. However, net sampling for obtaining biological information is performed at discrete points and its temporal and spatial resolutions are very low.

Although acoustic and net sampling from research vessels can be used to survey large areas, this approach is not suitable for observations of krill under winter sea ice, or continuous monitoring of krill at one or more locations. In these and other situations, krill may be sampled using echosounders deployed on platforms such as autonomous underwater vehicles (Brierley et al., 2002), gliders (Guihen et al., 2014), drifters, and moorings (Brierley et al., 2006). However, these platforms have a considerable limitation that biological information required for the interpretation of echo data is not available during acoustic sampling. Because net sampling is impossible on these platforms. As alternative tools, optical cameras useful for species identification and sizing are appropriate for the

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above platforms, but the observable range is very short.

To complement the limitations of net and optical sampling, it is necessary to infer biological information from echo data. One solution is to employ multifrequency or broadband echosounders. Warren et al. (2003) and Lawson et al. (2008) used a four-frequency echosounder and inferred the lengths and densities of euphausiids by a multifrequency inversion. Stanton et al. (2010) presented a more advanced approach. They used a modified commercial broadband echosounder and inferred the length and numerical density of elongated fluid-like scatterers. Notably, they measured a continuous spectrum of the transition region from Rayleigh to geometric scattering in the 30–100 kHz frequency range [Fig. 9 in Stanton et al. (2010)]. Such a continuous spectral shape enables us to infer the sizes of organisms more robustly. In addition to Stanton et al. (2010), a number of papers on the utilization of broadband signals for classification of scattering sources and inference of size, abundance, and orientation of marine organisms have been published (Stanton et al., 2003; Roberts and Jaffe, 2008; Lavery et al., 2010; Jaffe and Roberts, 2011; Leong et al., 2012; Ross et al., 2013). Broadband echosounders will become standard tools in future Antarctic krill surveys. The purpose of our study was to establish a method for inferring biological information from echo data by introducing broadband echosounders.

In this study, the volume-backscattering spectrum of an Antarctic krill aggregation was measured by a broadband echosounder and their length-density distribution was inferred by an inverse approach. Also, the signal-to-noise ratio (SNR) at each frequency was estimated and the measured volume-backscattering strengths were evaluated before inversion for accurate inferences. Furthermore we applied a theoretical scattering model of "simple" prolate spheroids to the inversion for the first time in the acoustical study of Antarctic krill.

2. Methods

2.1. Broadband echosounder

The broadband echosounder used in this study is almost identical to our previous system (Amakasu et al., 2013), but some modifications were made as follows. To increase the transmitting and receiving sensitivities of the previous transducer, the number of piezoelectric elements was increased from 30 to 52 in this study. Similar to the previous transducer, all elements are sandwiched between two acrylic-resin circular masses. However, in the new design, the actuators are densely arranged in a grid format. The elements sandwiched between two acrylic-resin circular masses are embedded in a PVC cylindrical housing (diameter 16.5 cm, height 16 cm) for waterproofing. The beam patterns at 38, 70, and 120 kHz of the transducer were measured in a tank and were compared with theoretical beam patterns. The main lobes of the measured beam patterns almost matched those of an (11-cm diameter) ideal circular piston source. The beamwidths at 20–200 kHz theoretically range from 41° to 4°. Although the transmission and reception were initially performed by a single transducer (Amakasu et al., 2013), the SNR of the echosounder was low presumably due to a transmit/receive switch. To improve the SNR, a pair of transducers were employed for separate transmission and reception. The transmit waveform generated by an arbitrary waveform generator (NF Corp., WF1946B) was amplified by a power amplifier (Accuphase Laboratory, Inc., PRO-100), and then sent to the transmitting transducer. The transmitted signal was a linear frequency-modulated signal with a frequency sweep of 20–200 kHz. The pulse duration and ping rate were 10 ms and 1 ping/s, respectively. Echoes received by the receiving transducer were amplified by a differential preamplifier (NF Corp., model 5307) before passing through a bandpass filter (NF Corp., model 3628: cutoff frequencies of 10 and 200 kHz). The output signals from the bandpass filter were digitized by a National Instruments (NI) data acquisition system with a 12-bit high-speed digitizer (NI PXI-5105: 500-kHz sampling rate) and a customized data-acquisition software in LabVIEW.

2.2. Echo processing

The volume-backscattering coefficients were obtained from the digitized data of the output signals from the bandpass filter. This section describes the processing procedure of the digitized data (here referred to as the echo waveforms). The procedure is largely based on Stanton et al. (2010).

The volume-backscattering coefficient $s_v(f)$ is expressed as [modified form of Equation (18) in Stanton et al., 2010]

$$s_v(f) = \frac{\left|V(f)\right|^2}{\left|K(f)\right|^2 \left|L^2(f)\right|^2 (ct/2) r^2 \Psi(f)}, \tag{1}$$

where f is the acoustic frequency, $V(f)$ is the Fourier transform of a compressed-echo waveform after pulse-compression processing (Chu and Stanton, 1998; Stanton and Chu, 2008; Stanton et al., 2010) in time gate t, $ct/2$ is the thickness of the sampling layer, c is the speed of sound in water, and $K(f)$ is the transmitting and receiving factor (Furusawa et al., 1993) which is the product of source pressure, receiving sensitivity of the receiving transducer, and receiver gain of the echosounder. $K(f)$ was determined in the system calibration (see next section). $L(f) = r^{-1} e^{ikr} 10^{-0.05\alpha(f) r}$ is the one-way transmission loss on a linear scale, where r is the range from the transducer to the half-thickness of the sampling layer, $k = 2\pi f / c$ is the wave number, and $\alpha(f)$ is the absorption coefficient in dB/m (Francois and Garrison, 1982). $\Psi(f)$ is the equivalent bean angle.

The vertical profile of $s_v(f)$ in each ping is obtained by the following procedure which was verified by a computer simulation (Amakasu, 2014).

1) Pulse-compression processing is applied to the echo waveform. The compressed-echo waveform is divided into t layers. In this study, we set t to 0.512 ms; therefore, $ct/2$ was approximately 0.38 m in the case of $c = 1500$ m/s, corresponding to 256 points at a 500 kHz sampling rate.
2) $V(f)$ in each layer is calculated. Although there are 256 points in each layer, the compressed-echo waveform in each layer is zero-padded to 512 points prior to Fourier transformation. Thus, the spectral resolution is approximately 1 kHz.
3) $s_v(f)$ of each layer is calculated by Equation (1). $\Psi(f)$ is given by the approximate expression $5.78/(ka_t)^2$ for an ideal circular piston source (Medwin, 2005). Here the transducer radius a_t is assumed as 5.5 cm which is half the effective diameter of the transducer (11 cm; see previous section).

2.3. System calibration

The transmitting and receiving factor $K(f)$ was determined by a calibration using a 15.9-mm-diameter (5/8″) standard sphere made of tungsten carbide with 6% cobalt binder. The 15.9-mm sphere was selected because its backscattering amplitude exhibits no sharp peaks or deep dips across the 20–200 kHz frequency band. Because our echosounder is not split-beam system, we cannot know the position of the sphere. Therefore, among many pings, we selected