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Effective and accurate use of difference in mean volume backscattering strength to identify fish and plankton

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Acoustic species identification is very important for fisheries' operations and surveys. One of the most promising methods for identification is to utilize the difference of mean volume backscattering strengths (ΔMVBS) among frequencies. Improvement of this technique is the aim of this study. The ΔMVBS must be obtained for a common observation range among frequencies so that the difference can be attributed solely to frequency characteristics of the sound scattering of targets organisms. We derived the common observation range of at least up to 150 m for our quantitative echosounder operating at 38 and 120 kHz with the same beam widths of 8.5°. We related ΔMVBS data obtained off northeastern Japan to specific marine organisms combined with the swimming depth and water temperature information. The echoes with small ΔMVBS (-1 dB<ΔMVBS<4 dB) were attributed to the walleye pollock (*Theragra chalcogramma*) and the echoes with large ΔMVBS (>10 dB) to krill (*Euphausia pacifica*). The changing pattern of ΔMVBS suggested complicated behaviour between species such as predator and prey interaction. In order to obtain reliable and detailed information the integration cell should be small and the ΔMVBS should be displayed as an echogram in an absolute colour scale.

Keywords: classification, difference of mean volume backscattering strength, observation range, quantitative echosounder.

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Introduction

Echo integration is the most important hydro-acoustic method for fisheries surveys being widely used for the purposes of estimating stock abundance, mapping geographical distribution, and obtaining ecological information. However, especially in a multi-species environment, significant error in biomass estimation may be caused in the species allocation of the mean-volume backscattering strength (MVBS). The echogram-scrutinizing method based on human experience is rather subjective (Reid *et al.*, 1998). Therefore, the species allocation has been done traditionally by referring to concurrent trawling data (Simmonds *et al.*, 1992). However, when schools are small or interspersed and the trawling has a low or varying catchability, net sampling is often unreliable even as a rough means of identification and prolonged trawling is time-consuming. If the acoustic identification of fish species was more reliable acoustic-abundance estimates would become more accurate, and surveys easier to conduct, because the number of confirmatory target-fish trawling operations could be reduced. Furthermore fishermen have been interested for a long time in being able to select the species or the size – or both – of fish in a target school before putting the trawl net over the side. Consequently increased reliability of the acoustic fish-species identification method has long been a worthwhile subject of investigation (Lawson *et al.*, 2001).

Several studies have identified fish species by employing the discriminant function analysis and/or artificial neural networks based upon features extracted from fish-school echoes, including morphological, bathymetric, and energetic characteristics (Weill *et al.*, 1993; Haralabous *et al.*, 1996; Scalabrin *et al.*, 1996; LeFeuvre *et al.*, 2000; Lawson *et al.*, 2001). This method becomes less effective when several species are mixed. Some other studies have employed wide-band echosounders to characterize the spectral signature of echoes of several fish species, and then processed the result by the discriminating methods (Simmonds *et al.*, 1996; Zakharia *et al.*, 1996). Echoes at discrete frequencies have also been shown with superimposed colours representing the frequency characteristics of marine organisms (Cochrane *et al.*, 1991). Also, backscatter echo envelopes have been analysed to investigate the internal structure of schools (Rose and Leggett, 1988; Scalabrin *et al.*, 1996). Several of these methods have provided high rates of correct classification in a limited number of conditions but none of them to date seem applicable over a wide range of time and space (Scalabrin *et al.*, 1996).

One of the most promising and popular techniques makes use of the difference of MVBS between several frequencies. We call the difference of MVBS ΔMVBS or MVBS difference. This method has been employed frequently to discriminate especially between plankters and other scatterers like fish (Saetersdal *et al.*, 1982; Cochrane *et al.*, 1991; Everson *et al.*, 1993; Madureira *et al.*, 1993; Miyashita *et al.*, 1997). This is possible because the echoes from plankton are more highly dependent on frequencies than the echoes from fish. A similar but different application of the frequency difference of scattering to larger zooplankton is called the two-frequency method and it depends on a scattering model to provide the body length (Greenlaw, 1979; Holliday and Pieper, 1980; Furusawa, 1990; Mitson *et al.*, 1996; Miyashita *et al.*, 1997).

The utilization of ΔMVBS should reveal the frequency characteristics of sound scattering by marine organisms. The method, however, needs to be refined to be more reliable and useful. For example, little consideration has been given to the observation ranges of the various frequencies and to the size of echo-integration cell used to obtain the MVBS. The frequency characteristics of echoes are caused not only by the target marine organisms but also by echosounder systems, sound propagation, and noise (Furusawa *et al.*, 1999). The examination of the observation range is necessary to extract reliable information on the frequency difference of scattering of the target organisms. In addition, a large integration cell may include a mix of different species of different sizes, making the ΔMVBS an unreliable tool for species identification.

The aim of this paper is to improve the MVBS difference method for species classification. We firstly examine the observation range of the echosounder to make the MVBS difference observation more accurate. We then derive the ΔMVBS over the common observation range from the volume backscattering strength obtained for small integration cells, display the results as an echogram with an easily discernible absolute colour scale and then try to classify into major species of marine organisms by means of ΔMVBS. We apply and examine the methods for survey data obtained off the northeastern coast of Japan.

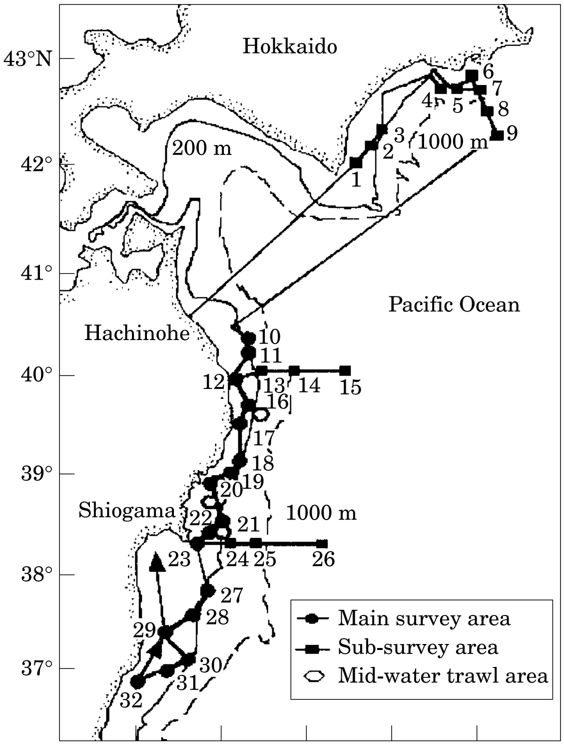

Figure 1. Survey transect lines with mid-water trawl locations (open hexigon) from off the Pacific coast of Hokkaido to off the coast of Jhoban surveyed by RV "Wakataka-maru", 15–25 April 1997. The numbers correspond to survey stations. A thin solid line shows the 200 m isobath, a long dotted line the 1000 m isobath.

Methods

Acoustic survey

An acoustic survey was conducted from 15 to 25 April 1997 between the Pacific coast of Hokkaido and the coast of Jhoban (Figure 1) by RV "Wakataka-maru", Tohoku National Fisheries Research Institute, Japan. Most of the acoustic transects were set along the 200 m isobath. Three mid-water trawling operations were targeted at acoustically identified krill and caught approximately 2, 3, and 10 kg of krill (*Euphasia pacifica*), with an average body length of 19 mm. CTD observations were performed at each survey station to obtain oceanographic and environmental information. The quantitative echosounder (Kaijo KFC-2000) employed in this survey operated at two frequencies (38 and 120 kHz) simultaneously. Since the beam widths were standardized to be 8.5° we could compare the scattering characteristics of target marine organisms between the two frequencies under nearly the same conditions. We collected ΔMVBS data at the two frequencies and utilized the data obtained for small integration cells with a period of 0.1 nautical mile sailed-distance and width of 1 m depth.

Observation range

In order to extract the true frequency characteristics of the target scatters the MVBS obtained by different frequencies should be compared at a common observation range that is independent of frequency-dependent noise and the directivity of the sounder (Furusawa *et al.*, 1999).

The observation range is determined by the signal-to-noise ratio (SNR). The SNR is expressed as a function of the target-fish parameters, the echosounder parameters, the acoustic propagation and the noise. Among noises, the noise generated by the survey vessel itself is generally the largest because of the vicinity of noise sources – mainly propeller-noise in the high frequency region – and that of the production of the propulsion power. We regard the SNR as the ratio of the echo power of the fish (school) to the received noise power of the survey vessel. The SNR (S_N) is shown as

$$S_N = \frac{P_F^2}{P_N^2} = \frac{P_0^2 10^{-0.2\alpha r}/r^4 b^2 T_S}{N_P^2 \Delta f / D_I} \tag{1}$$

where P_F is the echo pressure of fish (school), P_N is the noise pressure of the survey vessel, P_0 is the source pressure, α is the absorption coefficient (Francois and Garrison, 1982), r is the range to the target, b is the directivity function, D_I is the directivity index, T_S is linear value of target strength (abbreviated as TS), N_P is the noise spectrum level, and Δf is the bandwidth of the receiving system. We use decibel notation of the target strength, TS, and the linear notation, T_S, interchangeably and the relation is $TS = 10 \log T_S$. In this study, TS is defined not only for an individual fish but also for a fish school. The TS of the fish school is the average TS of an individual fish multiplied by the number of fish in the school.

Some parameters are expressed by more convenient parameters or by approximate expressions as followings:

$$N_P^2 = N_{P0}^2 f^{-1.8}, \tag{2}$$

$$D_I = \left(\frac{2\pi f a}{c}\right)^2, \tag{3}$$

$$P_0^2 = \frac{\rho c \eta W D_I}{4\pi}, \text{ and} \tag{4}$$

$$b \cong \exp\left\{-\left(\frac{\pi a}{\lambda}\right)^2 \theta^2\right\} \tag{5}$$

where N_{P0} corresponds to the noise spectrum level extrapolated to 1 Hz, f is the frequency, a is the transducer radius, c is the sound speed in seawater, ρ is the density of seawater, η is the electro-acoustic efficiency, W is the electric power input into the transducer, λ is the wave length, and θ is the angle measured from the beam axis. The N_{P0} should be adjusted both for vessel type and conditions. An example is 145 dB when a 220 t vessel was sailing with a speed of about 11 kt (Nishimura, 1969). As our quantitative echosounder is installed onboard the noise-reduced research vessel, we use the value of 135 dB. The equation (5) is an approximation only for the main lobe (Hamilton *et al.*, 1977) and is used to speed up computation but it is sufficient for the present purpose. By substituting equations from (2) to (5) into equation (1), we obtain the final SNR as

$$S_N = \frac{4\pi^3 P \eta W \exp\left\{-2\left(\frac{\pi a f \theta}{c}\right)^2\right\} a^4 f^{5.8} 10^{-0.2\alpha r} T_S}{c^3 r^4 N_{P0}^2 \Delta f} \tag{6}$$

The parameters used to compute the observation range for our echosounder are shown in Table 1. The observation range, that is the equi-SNR contour line, is derived as the pair of the slant range r and the angle θ where SNR is equal to a certain value, present case 10 dB. Among the above parameters the TS is difficult to assume because we encounter various organisms and must also consider the case when a peripheral part of large school begins to enter into the beam. Therefore it is necessary to examine observation ranges for various TS values and to adapt a conservative range. The observation ranges are derived at two frequencies for varying TS values while other parameters are kept constant.

Frequency characteristics of target strength

The MVBS difference method depends on the frequency characteristics of sound scattering by marine organisms. Broad-band scattering spectra of marine organisms is shown in Figure 2 (modified from Furusawa, 1991). These characteristics are approximate but can be used for the present purpose of a broad classification of organism types. The dorsal-aspect TS normalized by squared body length in cm, TS_{cm}, is shown as functions of the body length divided by the wavelength, L/λ, for bladder and bladderless fish respectively. Curves labelled (−5, 15) and (0, 10) are the averaged TS, when the tilt angle distributions are assumed to be normal with a

Table 1. The parameters needed to calculate the observation range of the quantitative echo sounder, Kaijo KFC-2000

Parameters varied with frequency				
Frequency	f	(kHz)	38	120
Electric power	W	(kW)	2.7	1
Radius of transducer	a	(cm)	13.5	4.3
Absorption coefficient	α	(dB km^{-1})	8.8	42.8
Beam width		(deg)	8.5	8.5
Other parameters				
Vessel noise	NP_0	(dB)		135
Band width	Δf	(kHz)		2.5
Electro-acoustic efficiency	η			0.5
SNR	SN	(dB)		10
Sound speed in sea water	c	(ms^{-1})		1500
Density of sea water	ρ	(kg m^{-3})		1000
Target strength	TS	(dB)		-20, -30, -40, -50, -60

mean of 5° head-down and 0° with a standard deviation of 15 and 10°, respectively. The normalized TS is generally higher at higher frequencies for bladderless targets. The normalized average TS decreases slightly at high frequencies for bladder targets. This is because as L/λ becomes large the main lobe in the TS pattern becomes sharp so that tilt angle variation increases the chance that small TS values will occur.

Since the average TS is applied for the echo integration method we use the averaged curves of bladder and bladderless fish. Small marine organisms without a swimbladder, such as krill, exhibit large differences in sound-scattering strength between 38 and 120 kHz, the two most commonly used frequencies in fisheries research. If the body length of the krill is 19 mm, as estimated from the three trawling operations of our survey, we observe a difference of 15 dB in TS_{cm} between 38 and 120 kHz based on the bladderless curve (Figure 2). The mean body length of the walleye pollock hauled in the vicinity of the coast of Sanriku (near station number 17) in 1996 was 17 cm. In contrast to krill, we found -2 dB of the TS_{cm} difference for 17 cm pollock (Figure 2).

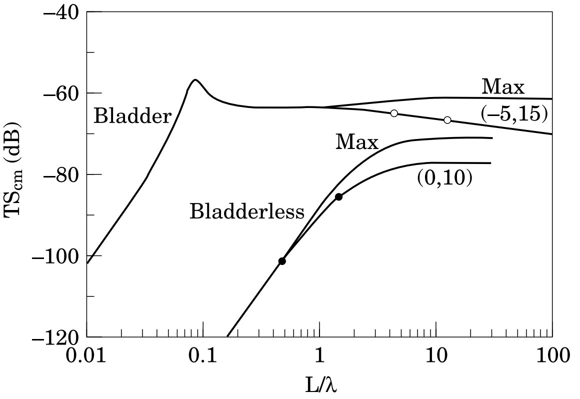

Figure 2. Normalized target strength, TS_{cm}, of bladder and bladderless fish, as functions of L/λ. Tilt-angle distribution of marine organisms is expressed by mean tilt-angle and its standard deviation pairs in parenthesis. Closed circles indicate the TS_{cm} of krill of body length 1.9 cm at frequencies of 38 and 120 kHz. Open circles show the TS_{cm} of walleye pollock of the body length 17 cm at the same frequencies.

The difference of mean volume backscattering strengths at two frequencies

The volume backscattering strength (abbreviated as SV) is shown in linear notation as

$$S_V = n\ T_S \tag{7}$$

where S_V is the linear value of SV and n is the distribution density. If the school is large compared with beam spreading the SV obtained for one ping represents the true density in the school. If this is not so then the SV does not always directly reflect the density. This is because the beam also "sees" vacant space and our equivalent beam angle used in deriving SV is defined for a large school. Because of this uncertainty we call the SV obtained for each ping "raw SV" in this paper. This problem is lessened in the echo integration method in which the raw SV are averaged to give the mean volume backscattering strength (MVBS) or the average SV. The MVBS gives the average density including vacant spaces in integration cells.

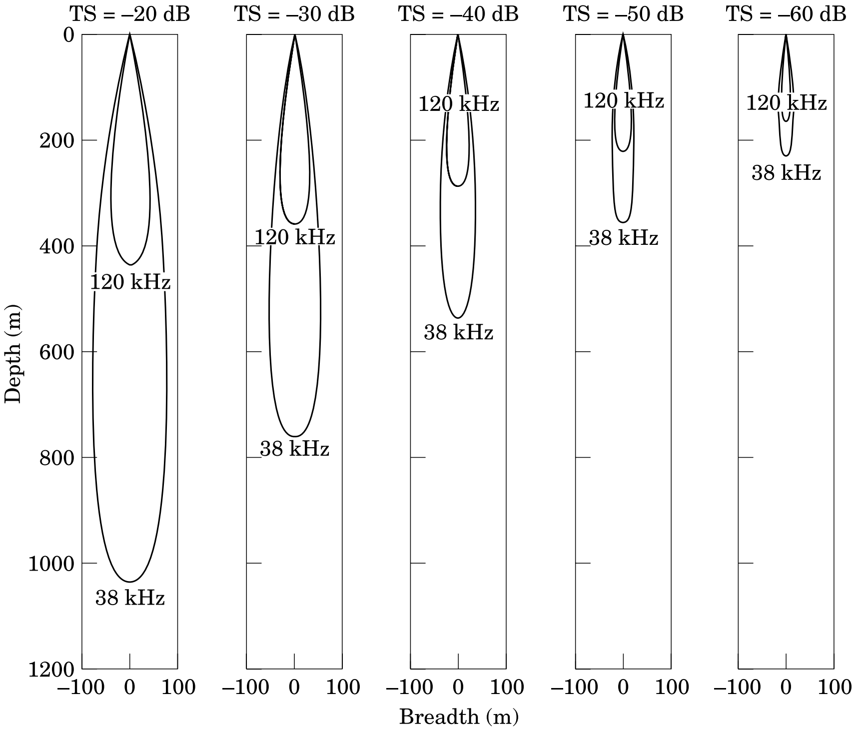

Figure 3. Observation ranges of the quantitative echo sounder, Kaijo KFC-2000, for varying TS values between − 60 and − 20 dB at 38 and 120 kHz.

The MVBS is frequency dependent because the TS is frequency dependent and we can write it as

$$\langle S_V(f)\rangle = n\ T_S(f) \tag{8}$$

emphasizing the frequency dependence on f [n and T_S in this equation are both averaged values differing from those in Equation (7)]. Making a ratio of MVBS between two frequencies deletes the common term of n and leaves a frequency dependent TS ratio. This ratio is the difference in the decibel notation (in this paper we use decibel and linear notation interchangeably). The principle of ΔMVBS method is to use the TS ratio in the classification of organism types and that of the two-frequency method is to use it for derivation of size mostly of zooplankton.

We use MVBS at two frequencies obtained in the common observation range, and the ΔMVBS is described as

$$\begin{aligned} \Delta\text{MVBS} &= \text{MVBS (120 kHz)} - \text{MVBS (38 kHz)} \\ &= \text{TS (120 kHz)} - \text{TS (38 kHz)} \end{aligned} \tag{9}$$

The ΔMVBS was derived by subtracting the MVBS of 38 kHz from the MVBS of 120 kHz, when the MVBS of both frequencies were larger than a given MVBS threshold, − 80 dB, in this study. When the MVBS of both or either frequency is smaller than the MVBS threshold we assume that there is no echo.

Results

It is necessary to compare the mean-volume backscatter of two frequencies (ΔMVBS) at a common observation range. The observation ranges depend on the TS of the scatterers and the acoustic frequencies (Figure 3). For example, when the TS value is − 20 dB, the maximum detection depth of 38 kHz is 1035.5 m and that of 120 kHz is 440.4 m. However, when the TS is − 60 dB the difference of the observation ranges for both frequencies is not as large. In general, the smaller the TS value, the smaller the observation range for both frequencies and the smaller the difference between frequencies. Both frequencies have a common observation range up to a water depth of 150 m regardless of TS values (Figure 3). In this common observation range we can compare the frequency characteristics of sound scattering of marine organisms.

The water temperatures at survey stations 6, 19 and 30 are shown in Figure 4. We grouped transect lines into three regions by the range of the water temperature. Firstly, the region off the Pacific coast of Hokkaido, survey stations from 1 to 9, showed the water temperature between 0 and 3°C. The second region is off

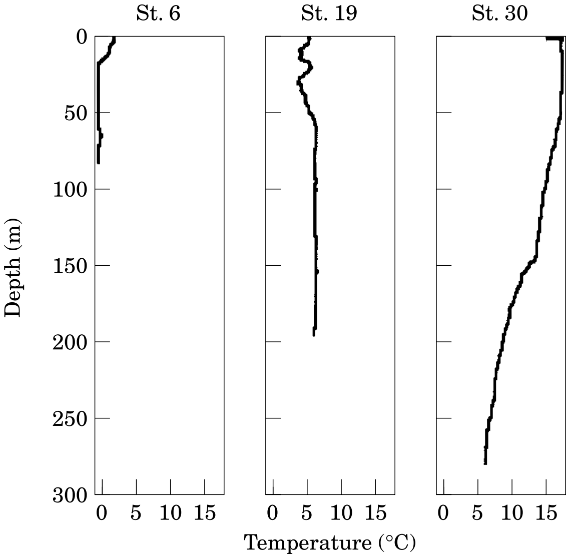

Figure 4. Profiles of the water temperature at survey stations 6, 19 and 30.

the coast of Sanriku, stations 10 to 27, with the water temperatures between 4 and 8°C. The third region is off the coast of Jhoban, after survey station 27, where the water temperature was approximately from 7 to 18°C.

To illustrate our techniques, Figure 5a and b show examples of MVBS echograms obtained between the stations from 10 to 13 at 38 kHz and 120 kHz respectively and the corresponding echogram-like display of ΔMVBS is shown in Figure 5c. These echograms display MVBS values in small integration cells along the transect lines. The echograms of 38 kHz and 120 kHz have the range of MVBS between − 90 and − 50 dB, while the echogram of ΔMVBS has the range of − 16 to 15 dB, both with 256 colour steps (Figure 5c). Course changes caused mountain-like or valley-like sea floor images and made stripe-like bubble echo images. The effect of noise is seen at depths deeper than about 200 m in the 120 kHz echogram (Figure 5b). In reading the echograms a common observation range should be taken into account. At shallower depths than 150 m, as discussed above, the ΔMVBS is considered to be caused solely by the frequency characteristics of the scatters of marine organisms. Especially for small or weak scatters the maximal common observation range should be taken into consideration in viewing these figures. This is shown by dotted line in ΔMVBS echogram (Figure 5c).

Echograms of only ΔMVBS in four areas are shown in Figure 6 with Figure 5c shown again as Figure 6b. In order to classify the species of marine organisms we used our ΔMVBS, bathymetry, and water temperature data. Echoes with small ΔMVBS between − 1 and 4 dB are distributed near the sea floor at stations between 6 and 7 in Figure 6a. From the TS characteristics the difference for walleye pollock was small and approximately − 2 dB in our case as shown in Figure 2. The water temperature in this transect line was approximately 0°C (Figure 4). It is known that walleye pollock are found close to the sea bottom at water temperatures between − 1 and 10°C (Abe *et al.*, 1999; Swartzman *et al.*, 1999). Hence the possibility that the echoes are of walleye pollock – the uppercase W letters – is high. On the other hand echoes with a large ΔMVBS, more than 10 dB, are seen in mid-waters and near the sea floor in Figure 6b. These echoes are distributed discretely over a broad range of regions. The TS difference for krill in our case was approximately 15 dB as shown above (Figure 2). The water temperature of this region was approximately 8°C (Figure 4). The krill are often found in mid-water of about 2.5–11°C, and specifically in waters of 6–9°C off Northern Japan (Nicol and Endo, 1998). For these reasons these echoes – the letters E – are possibly of krill). There are different kinds of echoes with small ΔMVBS between − 3 and 3 dB in the vicinity of the sea floor in the same echogram. These echoes are possibly of walleye pollock for the same reasons as listed above. The pattern of echoes in Figure 6c is similar to that of Figure 6b, suggesting the possibility that krill are distributed in middle waters discretely and walleye pollock near seabed.

In order to examine the possibility of ΔMVBS correspondence to krill, we tried to apply the two-frequency method. The method gives an estimate of dominant size, provided a single size class is assumed to dominate the acoustical scattering. By means of the two-frequency method, an equivalent spherical radius (e) for the dominant organism can be calculated from (Mitson *et al.*, 1996)

$$(\mathrm{ke})^2 = \frac{2}{3}\left[\frac{\mathrm{u}^4 - \mathrm{U}}{\mathrm{u}^2(\mathrm{U}-1)}\right] \qquad (10)$$

where

$$\mathrm{k} = \frac{2\pi \mathrm{f_m}}{\mathrm{c}},\ \mathrm{f_m} = (\mathrm{f}_{120} \times \mathrm{f}_{38})^{0.5},\ \mathrm{u} = \frac{\mathrm{f}_{120}}{\mathrm{f}_{38}}$$

and U is linear value for MVBS. The length of the krill is calculated from a regression relationship for euphausiid:

$$\mathrm{l} = \frac{\mathrm{e} - 0.0095}{0.134}\ [\mathrm{mm}] \qquad (11)$$

where e is in mm.

In the present study we classified ΔMVBS with more than 10 dB as krill. This was based on TS difference, approximately 15 dB, derived from Figure 2 as discussed

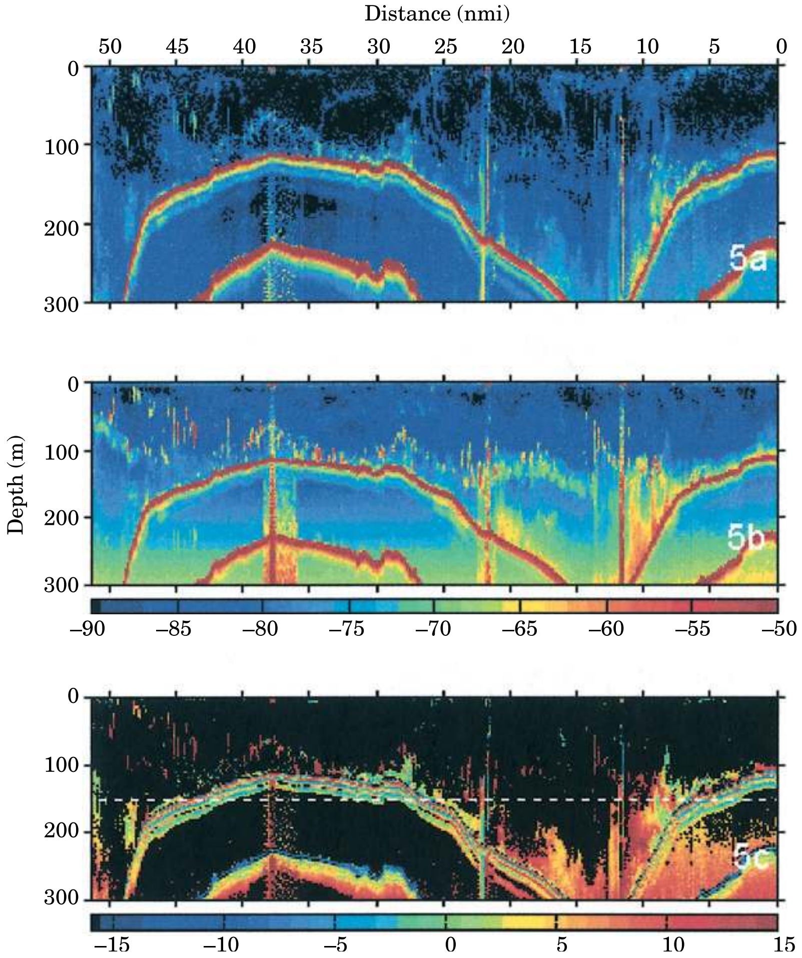

Figure 5. Echograms of the mean volume backscattering strength (MVBS) at 38 kHz (a) and 120 kHz (b) and of the ΔMVBS (c) at survey stations between 10 and 13. Vertical axes indicate the water depth in meters, and horizontal axes the sailed distance in nautical miles. The colour scales are inserted both for the values of the MVBS and of the ΔMVBS. In the echogram of ΔMVBS, the red shades represent stronger scattering at 120 kHz, and the blue shades indicate stronger scattering at 38 kHz. The white dotted line in the ΔMVBS echogram (c) shows the common observation range of 150 m. Caution should be paid in reading the echograms because sailing courses were changed sometimes as shown in Figure 1.

earlier. By changing ΔMVBS, from 10 to 15 dB by 1 dB step, Equation (10) gives equivalent spherical radii, and then Equation (11) provides lengths for the organism of 23.1, 21.5, 20.0, 18.5, 17.1, and 15.7 mm, respectively. Since the average body length from trawling, 19 mm, is within this range, the result supports our classification.

Discussion

Observation range

Marine organisms are not the only cause of the frequency characteristics of echoes: the echosounder system, noise, and acoustic propagation have frequency characteristics and they give frequency dependent echoes (Furusawa *et al.*, 1999). Therefore, echograms of a multi-frequency echosounder for fishing without any compensation for propagation loss should be interpreted carefully when one wishes to derive some information on frequency-dependent scattering.

The quantitative or scientific echosounder compensates for the propagation loss and recent echosounders display raw (not averaged or integrated) volume backscattering strengths (SV) which are also compensated for sensitivities and directivities. Therefore, the raw SV echogram is frequency independent and it even shows the true (within school) SV for fish schools much larger than the beam spreading. However for small schools or at the peripheries of schools and for dispersed fish it is difficult to compensate visually for the directivity. Making beam widths the same among frequencies is a simple way to make the comparison effective.

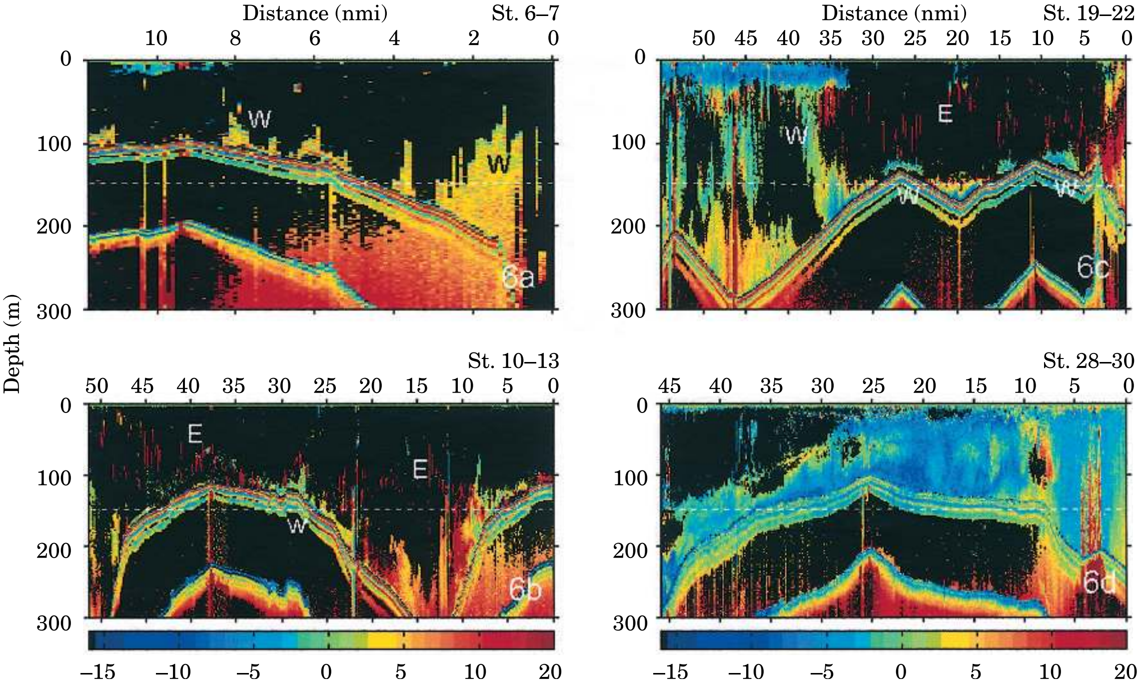

Figure 6. The echograms of ΔMVBS in four areas. Station numbers are shown at the top right on the horizontal axes. The colour scale corresponds to the value of the ΔMVBS. Echoes with red shades represent stronger scattering at 120 kHz, and those with blue stronger scattering at 38 kHz. The echoes with an uppercase letter "W" are attributed to walleye pollock, those with "E" to krill. Note that the horizontal scales are different for each echogram. As a result of a change in the ship course the echoes with a letter "W" in Figure 6c look like a boomerang.

The MVBS as the output of the echo integrator seems to be compensated for every frequency-dependent factor except TS but it is sometimes contaminated by frequency-dependent noise. This is why we must determine the observation range when we discuss the frequency characteristics of scattering. We propose the concept of the observation range to make the ΔMVBS method accurate. The user must know the observation range of the echosounder before applying the ΔMVBS method.

Changing pattern of ΔMVBS

The change of colour of ΔMVBS provides useful information on the interaction among species. Figure 7a comprises an enlarged section of Figure 6b that is about 0–11 nmi horizontally and 90–220 m vertically. Some red echoes with more than 10 dB of the ΔMVBS are shown very close to the seabed and others are displayed in green above them with nearly 0 dB of the ΔMVBS. We may imagine that krill might be distributed very close to the seabed and walleye pollock schools might be above them. Both echoes are gradually mix and this suggests some interaction between the two species such as prey and predator relation. The phenomenon is shown clearly around 8 nmi of the distance sailed. Towards the left echoes with an ΔMVBS of about 12 dB that are red to dark red only are seen and these may be considered to be krill schools only.

There are echoes with a stronger reflection at 38 kHz than at 120 kHz (up to − 10 dB) in Figure 6d. We do not have any other information that might allow us to hazard a guess at the species but the broadness of the distribution gives a hint for classification. Echoes near the hole in the above echogram are magnified and shown in Figure 7b. Those to the right of the hole have a ΔMVBS between 5 and 10 dB, suggesting some other organism. Their colours at the right side change gradually to merge into a more blue colour suggesting predator–prey interaction again. The hole in the huge echoes may have been caused by larger animals feeding on smaller prey.

Another interesting example is seen at near 35 nmi in Figure 6c. We observe apparently three species: a thin surface layer with ΔMVBS lower than − 5 dB, krill-like elongated schools with ΔMVBS about 10 dB and a pollock-like thick layer rising from the sea bottom to the surface layer. The ΔMVBS of the surface thin layer is very similar to the ΔMVBS for the broad school seen in Figure 6d, but we cannot guess the species. One possibility is a plankton with a gas sac that has a resonance near to 38 kHz.

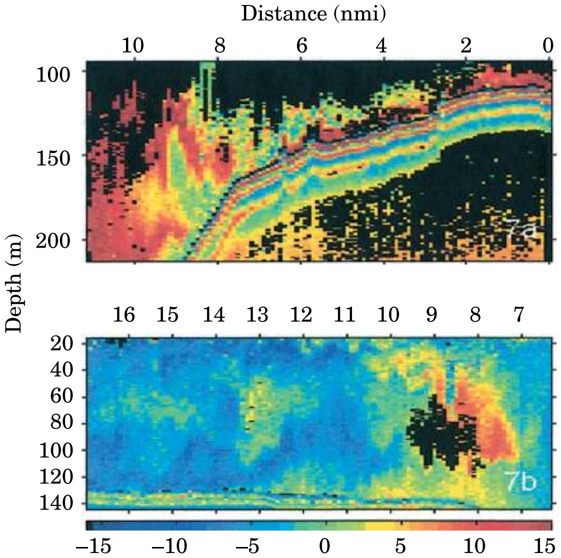

Figure 7. Echogram 7a is a section of Figure 6b about 0–14 nmi horizontally and 95–220 m vertically in size show at a larger scale. The echogram, Figure 7b, is similarly zoomed in on a section around a hole in Figure 6d. The gradual transition of colours suggests the interaction among species of marine organisms.

Frequency difference of scattering

We used rather generalized and approximate TS models to produce Figure 2. Our aims are diverse and it is difficult to know the actual species, size distributions and the orientations of all the schools so that it is also hard to predict accurate frequency dependences on TS.

Krill is bladderless and the frequency of 38 kHz is at the Rayleigh scattering region. The difference between 38 kHz and 120 kHz is very large and gives a good means of classifying but the TS of fish with swimbladders, like the walleye pollock, does not show sharp frequency dependence and the decrease of the TS at higher frequencies is mainly due to orientation dependence: the sharper the main lobe in the TS pattern and the broader the orientation distribution, the smaller the TS. Such small differences make classification of fish species problematic. Therefore, the ΔMVBS method is a more suitable method to classify the taxonomic level of plankton-like organisms than fish with swimbladders. However, as shown in Figure 7, the ΔMVBS echogram does highlight different species of organisms. Moreover the results derived by this study show that the ΔMVBS method is practically useful not only for the classification of marine organisms but also for inspection of the interaction between different species.

Species classification

Various information in acoustic data, non-acoustic data and *a priori* information are utilized for the purpose of classification of marine species. It is important to determine which information is effective for the identification process (Weill *et al.*, 1993) and to have some idea of the relative importance of each type.

Since we did not do any trawling for walleye pollock, it was impossible to know the distribution of body length and to derive a pertinent ΔMVBS range. By combining with other information such as water temperature and distribution depth, however, it was shown that the echoes with small ΔMVBS (-1 dB$<$ΔMVBS <4 dB, see echograms in Figure 6a, b and c) might be attributed to walleye pollock. Similarly the echoes with large ΔMVBS (>10 dB, see echograms in Figure 6b and c) were possibly from krill.

Many echoes with the ΔMVBS between -8 and -5 dB near the sea surface in Figure 6c could not be classified into species. Also unclassified is a large area of echoes with a ΔMVBS mostly between -9 and -5 dB and slightly between 3 and 7 dB in Figure 6d. Some plankters exhibit a strong reflection at lower frequencies and, considering the large area of their distribution (Figure 6c and d), the blue echoes might be such marine organisms. However it is difficult to distinguish species using only the ΔMVBS.

Detailed consideration on MVBS

When there are several species the MVBS is shown as

$$\langle S_V \rangle = \frac{1}{M} \sum_{j=1}^{J} \sum_{i=1}^{m_j} S_{vij} \tag{12}$$

where $\langle S_V \rangle$ is MVBS, M is ping number for one integration period, j is index for species, J is species numbers in one period, i is the number of pings, m_j is ping numbers where j-species appear and $S_{V_{ij}}$ is the raw volume backscattering strength (raw SV) for species j and ping i.

The simplest, and not so rare, case is that only one species appears continuously in a whole integration period with nearly the same raw SV. The ΔMVBS in that case is shown by Equation (8) and frequency difference of TS is given as shown by Equation (9).

The next simple case is that nearly the same raw SV of one species exists only in a part of integration period. The MVBS for that case is

$$\langle S_V \rangle = \frac{1}{M} \sum_{i=1}^{m} S_{V_i} = \frac{m}{M} S_V \tag{13}$$

As can be seen by Equation (13) the raw SV value is diluted by the space with no object. Therefore, the $\langle S_V \rangle$ is smaller than the S_V by the ratio m/M. The ratio of $\langle S_V \rangle$ obtained at two frequencies of f_1 and f_2 is

$$\frac{\langle S_V(f_1) \rangle}{\langle S_V(f_2) \rangle} = \frac{S_V(f_1)}{S_V(f_2)} = \frac{n}{n} - \frac{T_S(f_1)}{T_S(f_2)} = \frac{T_S(f_1)}{T_S(f_2)} \tag{14}$$

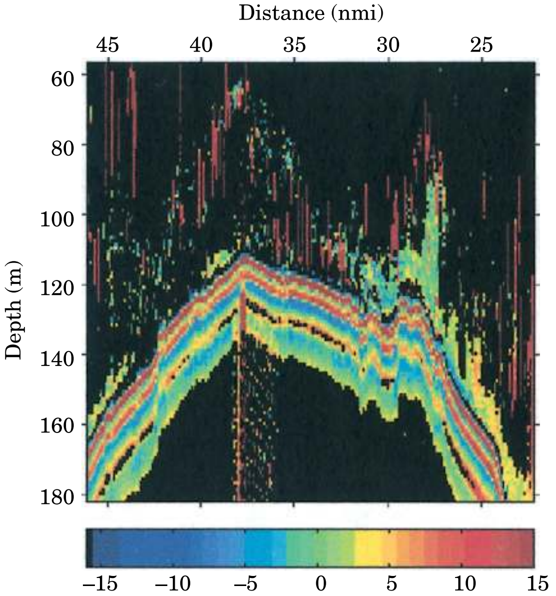

Figure 8. Echogram expanded from a part of Figure 6b some 22–46 nmi of sailing distance and 59–180.5 m of depth. The echoes appear in only one integration period and have stronger scattering at 120 kHz than at 38 kHz in middle water depth.

This shows that although the $\langle S_V \rangle$ value is different from the S_V value, the ratio of $\langle S_V \rangle$ at two frequencies correctly reflects the T_S ratio of the animals in the school. This ensures application of the ΔMVBS method to schools smaller than one integration period. Figure 8, which is expanded from a part of Figure 6b, 22–46 nmi of sailing distance and 59–180.5 m of depth, shows many "one period echoes" and the frequency difference correctly seems to show the TS difference of krill (about 12 dB).

Equation (12) shows the general case in which there are several species or size groups in one integration period. As the $\langle S_V \rangle$ is the mean value of many species in this case it is difficult to derive the T_S ratio from the $\langle S_V \rangle$ ratio as Equation (9). We have noted the gradual colour changes at the marginal areas of schools as is clearly seen in Figure 7. These phenomena reflect the mix of species. If we employ a large integration cell we are likely to observe a mixture of several different species of marine organisms. Therefore it is useful to employ a small integration cell for discriminating species (Madureira *et al.*, 1993).

Requirements of echosounder and processing

There have been several methods of displaying the ΔMVBS to discriminate species such as the direct comparison of echograms at several frequencies (Miyashita *et al.*, 1997), the scatter plot of the ΔMVBS (Saetersdal *et al.*, 1982; Everson *et al.*, 1993), the frequency distribution of the ΔMVBS (Saetersdal *et al.*, 1982; Madureira *et al.*, 1993), and superposition of RGB colours (Cochrane *et al.*, 1991). We used the colour echogram to display the absolute value of the ΔMVBS and confirmed that the method provides important information rather easily. We suggest that the echosounder used for this kind of study should have two or more frequencies; the beam widths of the frequencies should be the same and an absolute colour display of ΔMVBS in small cells, as in this paper, should be shown online.

Conclusions

The MVBS difference method proposed in this study is useful to discriminate planktonic organisms from swimbladdered fish. The classification trial,when combined with other information such as the water temperature and distribution depth, showed that small ΔMVBS (-1 dB<ΔMVBS <4 dB) was possibly attributed to the walleye pollock (*Theragra chalcogramma*) and large ΔMVBS(>10 dB) to krill (*Euphausia pacifica*). Also, the changing pattern of ΔMVBS may provide information on such things as predator and prey interaction among different species. It is a relatively simple and powerful method and can be put into practice routinely during acoustic surveys. Users are able to compare echograms directly and visually to sort organisms virtually in real time.

The ΔMVBS method utilizes different frequency characteristics of scattering. However observation ranges at different frequencies also depend on other frequency-dependent factors such as noise, directivity of the sounder etc. Therefore, in order to make the ΔMVBS method accurate, that is, to extract the true frequency characteristics of target scatterers, we propose that the comparison be carried out over a common observation range. In order to produce a large common observation range the sounder specifications for different frequencies should be as similar as possible and, above all, the beam widths should be the same.

In a large integration cell the ΔMVBS method becomes difficult to apply because it is highly likely that a mix of different species of marine organisms with various sizes will be found. Hence it is important to utilize a small integration cell for classification purposes.

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