FISHERIES SCIENCE 2008; **74**: 221–229

Verification of mean volume backscattering strength obtained from acoustic Doppler current profiler by using sound scattering layer

KYOUNGHOON LEE,[1]* TOHRU MUKAI,[2] DAEJAE LEE[3] AND KOHJI IIDA[2]

[1]*Fisheries Engineering Team, Fisheries Resources Department, National Fisheries Research and Development Institute, Busan 602-092, Korea,* [2]*Laboratory of Marine Environment and Resource Sensing, Graduate School of Fisheries Sciences, Hokkaido University, Hakodate, Hokkaido 041-8611, Japan, and* [3]*Department of Marine Production System Engineering, Pukyong National University, Busan 608-737, Korea*

ABSTRACT: Acoustic Doppler current profilers (ADCPs) have recently been used to estimate the dynamic characteristics and biomass of sound scattering layers (SSLs) or swimming speed of fish schools and to analyze SSL spatial distribution or various behavior patterns. This paper shows that it is necessary to verify mean volume backscattering strength (MVBS, dB) values acquired from each beam for quantitative analysis of the spatial distribution or the biomass estimates of such specific targets as SSL or a fish school when using an ADCP. In this study, the SSL was selected to be a homogeneous density layer over a large area and two methods were used to verify the MVBS values from each beam of the ADCP. First, a mutual comparison among four beams was conducted after calculating MVBS from the measured echo intensity. Second, the MVBS values were verified using comparison between the calculated MVBS from the 153.6 kHz ADCP and MVBS from three frequencies of a well-calibrated scientific echosounder. Moreover, the dominant scatterers (euphausiids) were collected by a framed midwater trawl. From these samples, biological data were used to identify the different frequency characteristics between two systems, using a distorted-wave Born approximation (DWBA) theoretical backscattering model in order to assess the averaged target strength and target strength TS differences for the three frequencies.

KEY WORDS: ADCP, DWBA theoretical backscattering model, euphausiids, mean volume backscattering strength, scientific echosounder, verification.

INTRODUCTION

The acoustic Doppler current profiler (ADCP) is an instrument that measures speed and direction of current flow using the Doppler shift of backscattered sound waves from suspended particles. The instrument has been applied in the field of fisheries acoustics and biological oceanography in recent decades. Many researchers have studied the vertical migration of sound scattering layers (SSLs) during their diel vertical migrations.[1,2] Also, the biomass of zooplankton and nekton mixed in the SSL has been estimated using mean volume backscattering strength (MVBS) produced by echo intensity obtained from ADCPs.[3,4] Information has been obtained on the swimming speed of fish schools using three-dimensional velocity measured by shipboard and moored ADCPs.[5,6]

Commercial ADCPs commonly use three or four transducers slanted 20° or 30° from the vertical.[7] Because of this geometry, it is very difficult to calibrate each beam *in situ* using the standard sphere technique as used for a scientific echo sounder.[8] In the case of a moored ADCP, each transducer beam can be well calibrated in a large enough water tank. For shipboard ADCPs, it has been shown to be possible to compare MVBS from a shipboard ADCP with that from a well-calibrated scientific echosounder.[9]

To estimate the density and dynamic characteristics of SSLs using ADCP, the MVBS equation,[9] which was proposed by RD Instruments, has made it possible to estimate zooplankton abundance in the SSL and compare the results with a multiple open–closing sampling net and theoretical

*Corresponding author: Tel: 82-51-720-2574. Fax: 82-51-720-2586. Email: khlee71@nfrdi.re.kr
Received 8 September 2007. Accepted 18 September 2007.

doi:10.1111/j.1444-2906.2008.01516.x

scattering model prediction given a knowledge of the species present.[4] However, it is necessary to verify MVBS values acquired from each beam for a quantitative analysis of the spatial distribution or the biomass estimates of a specific target when using an ADCP. Further, the scattering must satisfy such conditions that the SSL would be distributed evenly over a wide extent for the volume ensonified by each beam.

In this paper, this conditional SSL was chosen and the relative calibration method for each beam's MVBS was conducted using the comparison between each beam mutually. Furthermore, the absolute calibration method was verified using a comparison with the MVBS measured by a well-calibrated scientific echosounder.

MATERIALS AND METHODS

Measurements were carried out in the offshore Funka Bay area of Hokkaido, Japan, where the distribution of SSLs was confirmed over a wide area using the T/S Ushio Maru from April to December 2003. The installed ADCP is the Ocean Surveyor (153.6 kHz, RD Instruments, San Diego, CA, USA). Figure 1 shows the configuration of the four beams. The mechanical alignment of the traditional transducer head is decided by the reference point of Beam 1 at 45° relative to the ship's fore-to-aft centerline with Beam 4 at 135°, Beam 2 at 225° and Beam 3 at 315° relative to the centerline.

Raw echo intensity data (E) were collected at 1 or 2 s intervals for 120 depth bins, with each bin-length of 4 m. Echo intensity was displayed in units of 'counts' on a nominal logarithmic scale with a resolution of 8 bits, and they were input to a personal computer by binary code along with the ship's position and direction data set obtained using a GPS and a gyrocompass. The raw data were processed using TrackView v1.0.2c (SEA Corp., Chiba, Japan) for broadband ADCP with 1 or 2 minute-averaged times, and by using the following equation to analyze in MVBS values (dB/m^3) for each beam:

$$\mathrm{MVBS} = 10\log_{10}\left\{\frac{4.47\times10^{-20}K_2K_S(T_X+273)(10^{K_C(E-E_r)/10}-1)R^2}{C_SPK_110^{-2\alpha R/10}}\right\} \quad (1)$$

where r is the slant range from the transducer to a depth cell (m), K_2, K_S, K_C, K_1 are constants of each system using measured values supplied by the RDI company.[10] In addition, the temperature of transducer T_X (°C), noise level E_r (counts) and sound velocity C_S (m/s) were input by calculating measured values of temperature and salinity using a conductivity–temperature–depth (CTD) system (SBE-19 Plus, Sea-Bird, Bellevue, WA, USA) from April to December 2003. The absorption coefficient α was 0.033–0.055 (dB/m) in analyzed data (Table 1).[11]

In this study, the noise level E_r was defined as the 'reference level' because it is a very important parameter for calculating the MVBS value; it is usually set to be the smallest count within the dataset.[10] Consequently, as the reference level measured similar values on each of the four beams relative to each month, they were set as 20, 18, 15 and 15 for each beam, respectively. The calculated MVBS echogram was displayed as each of the four beams using the Surfer program v.7.02 (Golden Software, Golden, CO, USA).

The volume backscattering strength (SV, dB/m^3) data were collected by an EK 60 system (Simrad, Kongsberg, Norway) at 38, 120 and 200 kHz to compare with that of the ADCP. As SV are averaged to give MVBS or the average SV in integration cells, data were analyzed as average SV values (dB/m^3) extracted over the sampling interval of 1 or 2 minute-average times and the same bin length of 4 m as the ADCP. Acoustic interference noise signals that occurred at 120 kHz in the EK 60 were removed using EchoView software v2.25 (SonarData Ltd, Hobart, Australia).

To identify the animals responsible for the dominant scattering in the survey area, framed midwater trawl (FMT) surveys with a net mouth opening of 4 m^2 were carried out at a speed of approximately 3 knots. The trawl samples were preserved

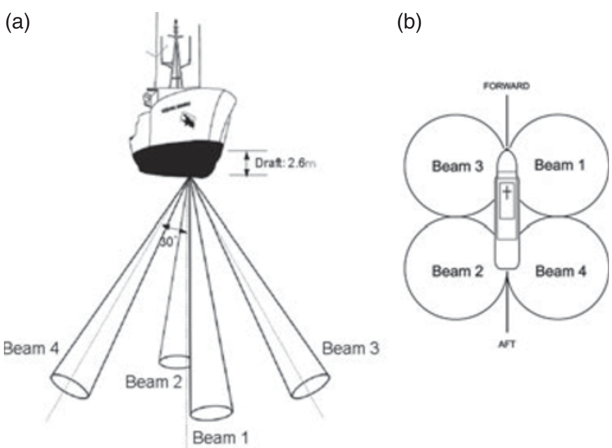

Fig. 1 (a) Arrangement of acoustic beams of the acoustic Doppler current profiler (ADCP) installed on the T/S Ushio Maru, and (b) example of a transducer configuration rotated –45° from the ship centerline (vessel mounted type by RD Instruments[7]).

Table 1 Parameters used to calculate mean volume backscattering strength (MVBS) value for acoustic Doppler current profiler (ADCP) data collected at depth of 20–30 m in the center of the sound scattering layer during 2003

	Temp. (°C)	Salinity (‰)	Sound speed (m/s)	$a^{\dagger}$ (dB/m)	pH
April	2.0	32.7	1455.2	0.033	8.0
May	4.6	32.6	1466.2	0.035	8.0
June	10.0	33.1	1487.8	0.044	8.0
July	12.4	32.7	1495.7	0.047	8.0
August	16.5	33.3	1509.7	0.054	8.0
September	16.9	33.2	1510.8	0.055	8.0
November	12.7	33.7	1498.0	0.049	8.0
December	10.7	33.9	1491.3	0.046	8.0

†absorption coefficient.

in 5% borate-buffered formalin. Oceanic environmental data were measured using a CTD at the station to characterize the hydrographic conditions. Temperature and salinity data were used to calculate the absorption coefficient, for the frequencies of the two acoustic systems.

RESULTS AND DISCUSSION

Echograms of ADCP and EK 60

Figure 2 shows echograms of MVBS calculated from echo intensity for each of the four beams of the ADCP and three echograms of MVBS converted concurrently at 38, 120 and 200 kHz by the scientific echo sounder. This example (bin size 4 m depth × 2 min) is selected from an SSL distributed comparatively extensively and evenly over the four-beam measurement area in May 2003. On examining each beam's echogram from the ADCP, it is immediately clear that Beam 4 indicated a higher MVBS than the other three beams, which are similar to each other. The comparison among the four beams for the ADCP leads to a relative verification among beams. In Figure 2, the echogram of Beam 4 is most similar to those at 120 and 200 kHz from the scientific echo sounder in relation to features and absolute values. Thus, the MVBS values from Beam 4 are needed to verify the reference of the four beams of the ADCP and to confirm the acoustic scattering characteristic of the dominant zooplankton in SSLs.

Comparison of Four Beams of ADCP

To confirm the correlation between the four beams for the ADCP, a comparison of MVBS between Beams 1–3 and Beam 4 is shown in Figure 3. As shown, the assumption that SSL ranged extensively in the same bin size was satisfied because these correlations were coincident with three beams on the basis of Beam 4 ($R \geq 0.95$). Further, there is an offset between the three beams ranging 4.6–7.2 dB.

In order to verify the correlation for other months in 2003, the relationship between the four beams' MVBS values, which are measured and calculated every month, is shown as Table 2. Each entry corresponds to data collected from evenly distributed SSLs for 3 h, and each MVBS was averaged at the targeted depth layer of 20–30 m. During 2003, MVBS from Beam 4 was known to be higher than that from any other beam. In addition, the correlation coefficient (R) and standard error (SE) of mean indicate that the scatterers were distributed evenly over the four beams in order to select data in the satisfied condition. It suggests that when the standard error is lower, scatterer distributions over the measured area are the more similar. When considering relatively good agreement ($R \geq 0.9$) in the required distribution between beams, it is satisfied in May, July, September and November. However, in July, SE values are shown in relatively large offset, so 3 months meet the above condition. To decide the relationship between the four beams, the MVBS of three beams with respect to Beam 4 were calculated in the averaged data (3.6, 5.2 and 4.8 dB) for 3 months. Calculating MVBS values over Beams 1–3 used the assumed ratio (0.46 dB/count) between MVBS and echo intensity counts that is proportional to the logarithm of power and converted to dB units. Thus, the relative calibration was conducted by subtraction of echo intensity as 8, 11 and 10 counts for the determined reference levels (E_r = 20, 18 and 15) applicable to the three beams, respectively.

If the SSLs were distributed evenly and extensively, the averaged MVBS must be the same for each of the four beams using the average over a long time in the wide survey area. As there are differences in the offsets of each beam, as shown here, ADCPs need to verify the relationships between beams prior to calibrating MVBS from each beam.

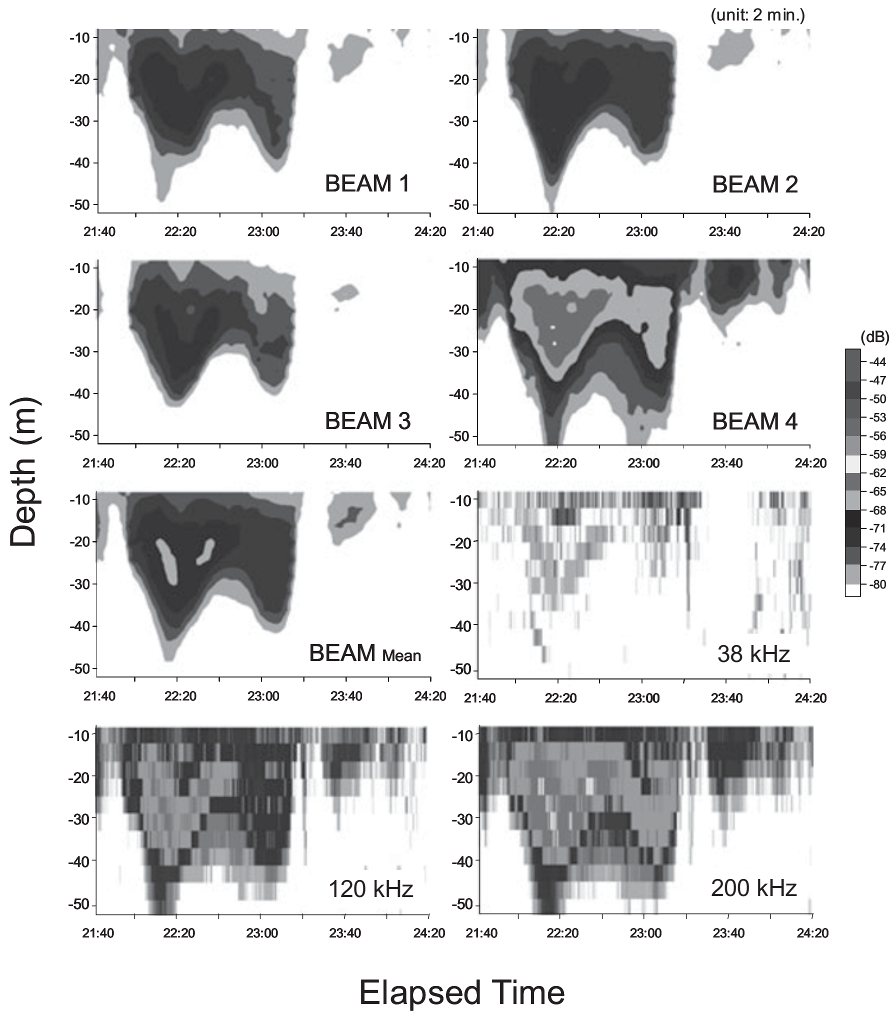

Fig. 2 Echograms obtained by mean volume backscattering strength (MVBS) from each beam of the ADCP (reference level, E_r = 20, 18, 15 and 15, respectively) and scientific echo sounder (EK 60) with a 4-m cell size in May 2003.

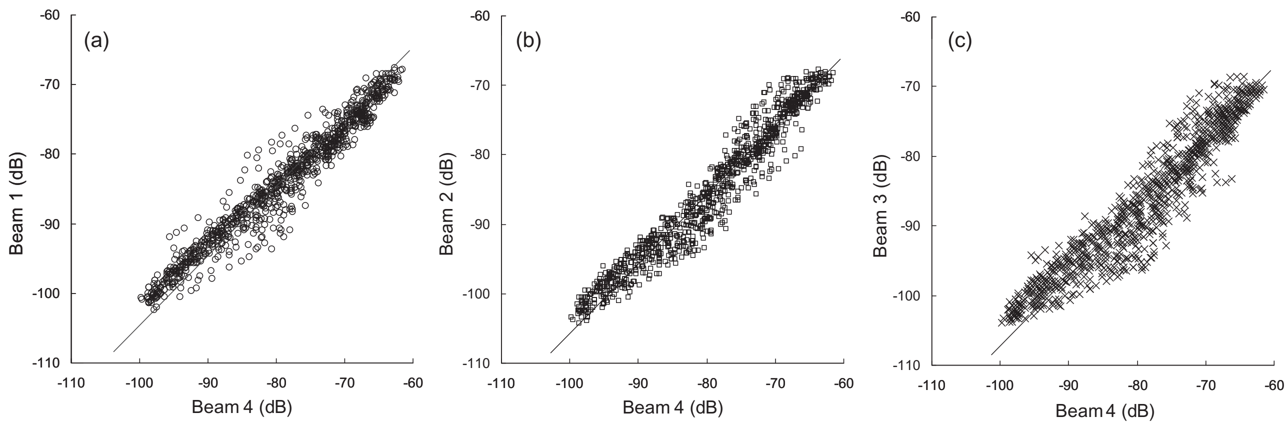

Fig. 3 Cross-correlation scatter plots of the MVBS from (a) Beam 1 = x – 4.6 dB (R = 0.96, standard error, SE 2.45 dB), (b) Beam 2 = x – 5.8 (R = 0.97, SE 2.37 dB), and (c) Beam 3 = x – 7.2 (R = 0.95, SE 3.17 dB) against that from Beam 4.

Verification of Four Beams of ADCP

To verify the backscattering strength obtained from the four beams of an ADCP, values were compared with MVBS data collected over a concurrent period of time using a scientific echo sounder. Figure 4a shows time series data of MVBS from the EK 60 (120 and 200 kHz) and MVBS from the

Table 2 Relationship between mean volume backscattering strength (MVBS) measured from four beams of the acoustic Doppler current profiler (ADCP) in the selected sound scattering layer during 2003

	200304				200305				200306				200307			
ADCP	Mean	Correlation coefficient	Standard error	Deviation	Mean	Correlation coefficient	Standard error	Deviation	Mean	Correlation coefficient	Standard error	Deviation	Mean	Correlation coefficient	Standard error	Deviation
Beam 1	−87.51	0.81	2.17	−3.23	−86.70	0.97	1.75	−3.94	−81.88	0.83	6.41	−2.44	−88.27	0.94	2.53	−4.29
Beam 2	−88.25	0.73	2.26	−3.63	−87.94	0.98	1.54	−5.18	−86.88	0.84	6.16	−7.44	−90.95	0.93	2.90	−6.98
Beam 3	−89.27	0.68	2.31	−4.45	−88.58	0.97	1.99	−5.82	−86.60	0.76	6.94	−7.16	−91.89	0.92	3.00	−7.91
Beam 4	−84.45	–	–	–	−82.76	–	–	–	−79.44	–	–	–	−83.98	–	–	–

	200308				200309				200311				200312			
ADCP	Mean	Correlation coefficient	Standard error	Deviation	Mean	Correlation coefficient	Standard error	Deviation	Mean	Correlation coefficient	Standard error	Deviation	Mean	Correlation coefficient	Standard error	Deviation
Beam 1	−86.45	0.79	2.00	−4.40	−75.10	0.97	1.69	−3.65	−75.75	0.92	1.27	−3.31	−82.64	0.89	2.43	−2.11
Beam 2	−88.82	0.82	2.02	−6.76	−76.86	0.98	1.53	−5.40	−77.61	0.93	1.29	−5.17	−85.17	0.91	2.07	−4.65
Beam 3	−89.20	0.73	2.41	−7.14	−76.08	0.96	2.02	−4.62	−76.62	0.93	1.30	−4.18	−83.98	0.89	2.55	−3.46
Beam 4	−82.05	–	–	–	−71.46	–	–	–	−72.44	–	–	–	−80.52	–	–	–

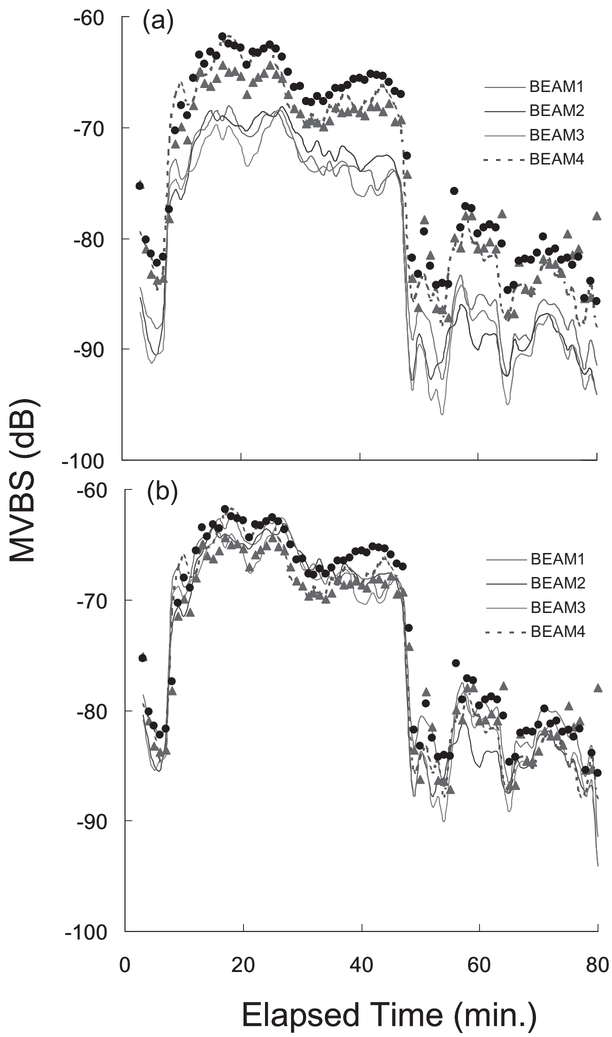

Fig. 4 Comparison of temporal variation of MVBS from the sound scattering layer at 25-m depth obtained by each beam of ADCP (153.6 kHz) and those from the scientific echo sounder at 120 Hz (▲) and 200 kHz (●). (a) Irregularities in the beam sensitivity, and (b) irregularities adjusted for the scientific echo sounder.

ADCP's four beams for the 25-m depth layer. As shown in Figure 4, while the MVBS records tend to have reasonably similar patterns overall, each beam, except for Beam 4, has differences in detail and in offset. So, the MVBS values from three beams need to be reconciled with Beam 4 by relative calibration, as discussed earlier, to give the time series after relative calibration shown in Figure 4b. This clearly illustrates the very close relationship between time series data; there is little difference in the comparable time series patterns between ADCP and EK 60 data.

However, there is a need to consider the frequency characteristic of the scatterers in the SSL. This can be done with knowledge of the animals

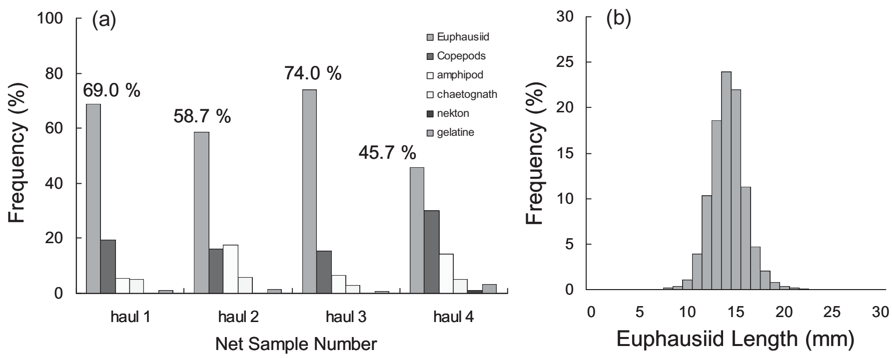

Fig. 5 Histograms of (a) total wet weight during the framed midwater trawl (FMT) net sampling, and (b) body length-frequency distribution of euphausiids caught using an FMT in conjunction with the acoustic observations ($n = 4523$, mean = 13.7 mm, standard deviation 1.79).

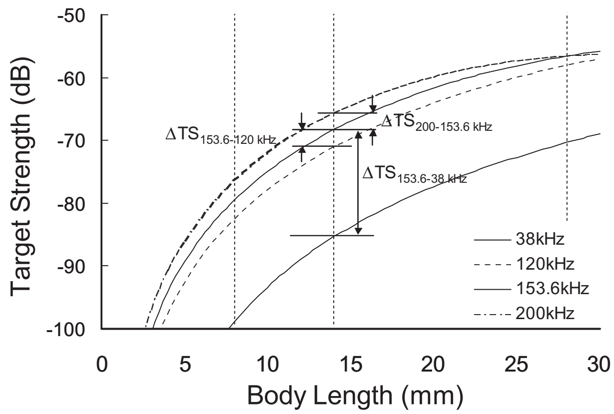

Fig. 6 Target strength for euphausiids ranging 8–28 mm body size using a distorted-wave Born approximation (DWBA) scattering model. The dB difference ranges of three frequencies relative to the ADCP 153.6 kHz for the mean body length (14 mm) are shown. Vertical dotted lines indicate the range of sampled euphausiid lengths; TS, target strength.

forming the SSL. The composition ratio of the SSL collected using the FMT surveys in May 2003 is shown in Figure 5. The net results showed that the SSL was comprised of euphausiids *Euphausia pacifica*, copepods *Calanus cristatus*, amphipods *Parathemisto japonica*, chaetognaths *Sagitta elegans*, and gelatinous zooplankton. The dominant animals within the sound scattering layer in each haul were euphausiids (mean wet weight 61.8%). The lengths of the euphausiids ranged 8–22 mm, and the mean body length was 13.7 mm as shown in Figure 5b.

To obtain the acoustic frequency characteristics of euphausiids, a distorted-wave Born approximation (DWBA) theoretical backscattering model[12] was used to estimate its target strength and target strength (TS) difference for the four frequencies. Figure 6 shows target strength (dB) calculated from body length (L) for each acoustic frequency. The position vector was obtained by digitizing captured euphausiids and measured their 2D morphology. The density contrast (g) and sound speed contrast (h) of euphausiids were estimated as 1.033 and 1.043 measured by the 'density bottle' and 'time of flight' methods, respectively.[13]

The utility of the ADCP was assessed by comparison with three frequencies of an EK 500 using echoes recorded from Antarctic krill *Euphausia superba*.[14] However, the SSL in this study contains various zooplankton and nekton. The dominant scatterer was discriminated from others in the SSL on the basis of the difference in acoustical scattering characteristic between two frequencies. The frequency difference method is used for analysis of acoustical scattering characteristic relative to identical scatters between high and low frequencies.[15] The difference of backscattering strength between frequencies is not so large for fish that have a swimbladder. In the case of swimbladderless or small zooplankton organisms, however, the difference is rather large. Especially, if the ratio of body length to wavelength (L/λ) is less than 1, the backscattering strength increases drastically with the ratio. The dominant scatterer was assumed to be rather small plankton in the SSL, because its backscattering strength is considerably higher at 120 and 200 kHz than 38 kHz as shown in Figure 2.

To identify the euphausiid group from the virtual echogram, the difference in backscattering strength was calculated at the three frequencies (38, 120 and 200 kHz) of the scientific echo sounder and 153.6 kHz of the ADCP. Species identification depends on the ratio of MVBS between two frequencies being equal to the frequency-dependent TS ratio for the body length (L), and the dB difference described as:

$$\begin{aligned}\text{dB difference} &= \mathrm{MVBS}(f_{\mathrm{High}}, L) - \mathrm{MVBS}(f_{\mathrm{Low}}, L)\\ &= \mathrm{TS}(f_{\mathrm{High}}, L) - \mathrm{TS}(f_{\mathrm{Low}}, L)\end{aligned} \tag{2}$$

where f_{High} is high, and f_{Low} is low frequency.

To identify targeted scatter by acoustical data, net sampling data gives important distribution and frequency characteristics of the dominant scatterers.[16]

Table 3 Ratio of measured mean volume backscattering strength (MVBS) relative to the number of extracted euphausiid cells on the basis of frequency difference TS ($\Delta TS_{200-38kHz}$) calculated using a distorted-wave Born approximation (DWBA) backscattering model

dB difference (kHz)	Classified euphausiids		
	Theoretical range	Measured cells of ΔMVBS	
	ΔTS (dB)	Total no. in cell	Ratio of cells (%)
200 – 38	13.5–23.7	171	100.0
200 – 120	1.7–6.1	165	96.5
120 – 38	11.8–17.6	158	92.4
200 – 153.6	0.2–3.0	148	86.5
153.6 – 38	13.3–20.7	139	81.3
153.6 – 120	1.5–3.1	45	26.3

However, systematic error can occur in analysis using a two-frequency difference method for its sampled size distribution; for example, errors arise due to avoidance from the sampling gear, the matching problem of acoustic data, and because there are patchy schools of macro-zooplankton, which have swimming ability. Therefore, there is difficulty in hauling all that we see using echosounder. In addition, frequency of net hauls is important to know its size distribution. Therefore, with reference to net sampling data at the same survey area in May 2002, the size distribution of euphausiids is estimated to be the range 8–28 mm (mean 14.0 mm, standard deviation 3.2 mm) and the frequency difference characteristics of dB difference between MVBS values of the ADCP and the scientific echo sounder can be ranged to minimum and maximum sizes of euphausiids.

A classification of euphausiids conducted on the basis of two-frequency difference ($\Delta TS_{200-38\,kHz}$) is shown in Table 3 and Figure 7. The classified euphausiid group was shown as the distributed cell ratio from each echogram for difference values between each frequency. For the dB difference characteristic at three frequencies from a scientific echo sounder, the ratio of the classified euphausiid cell at two frequencies has a difference in $\Delta TS_{200-120\,kHz}$ (96.5%) and $\Delta TS_{120-38\,kHz}$ (92.4%). These small deviations of dB difference can be produced by non-discarded noise at 120 kHz. There remained background noise made by frequency interference that was rejected. The leading causes of this noise are interference with a similar frequency of the ADCP, and by mixed scatterers distributed in the SSL. However, it is at a reasonable level in the ratio of cells, which are calculated by dB difference.

For comparison with the ADCP, that ratio is lower than that compared to $\Delta TS_{200-38\,kHz}$. The difference can be primarily affected by incident angle of four beams on the sound scattering layer. It means that there can be a deviation between theoretical dB difference characteristics and *in situ* measured MVBS difference for euphausiid cells.

The relationship between the combined MVBS from ADCP and the EK 60 for the classified euphausiid cells is shown in Figure 8, in order to verify absolute calibration of ADCP. The adjusted R-value was obtained between the ADCP and the three frequencies of the echosounder ($R \geq 0.96$). In the regression line, the deviations of 38 and 200 kHz relative to the ADCP at 153.6 kHz were -14.41 ± 1.33 and $+1.27 \pm 0.89$ dB, respectively. They were within the limits of theoretical dB difference frequency values, whereas the deviation of 120 kHz was -1.07 ± 0.92 dB, which was outside the range of theoretical dB difference. On this effect, Brierley *et al.*[14] suggested that it might be influenced by the difference in angle of beam orientation of two systems; however, the leading cause in this paper is the effect of the interference produced by similar frequency.

Other possible errors can be inferred from the deviation, such as a comparison between three frequencies for scientific echosounder. From this research, we found that no single set of density contrast or sound-speed contrast measurements is sufficient to characterize the material properties of zooplankton, since they vary between species as well as taxa. A more comprehensive study is needed to evaluate the seasonal, spatial and life-history variations in the material properties of zooplankton and the relationship with their biochemical composition.

However, these relationships indicate that the MVBS from ADCP can provide data for a valid estimation of zooplankton, if only to solve the problem of discriminating classified targets for a single frequency in the ADCP.

CONCLUSION

When exploring the correlation between zooplanktonic organisms and their marine environment,

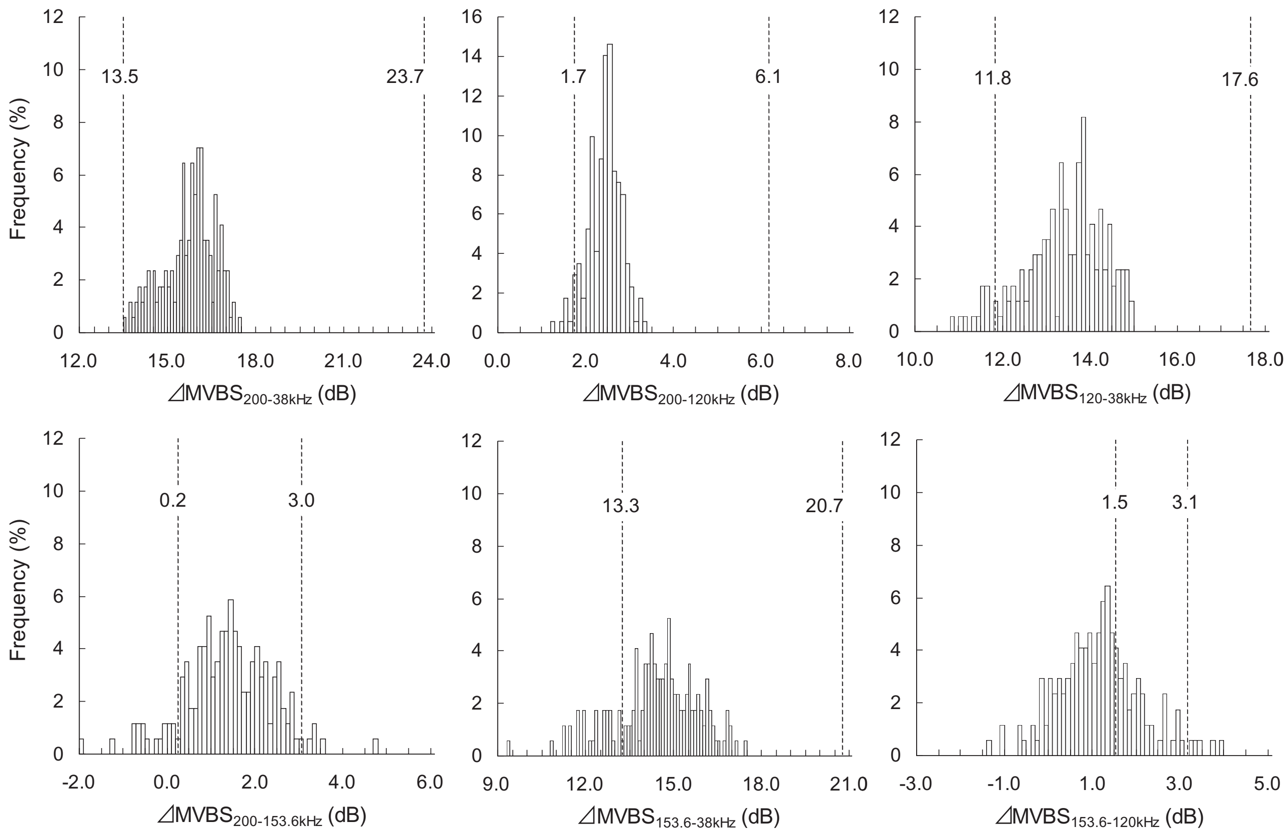

Fig. 7 Histograms of dB difference for the extracted euphausiid cells comparing ADCP (153.6 kHz) to EK 60 (38, 120 and 200 kHz). Dotted vertical lines represent each theoretical dB difference range.

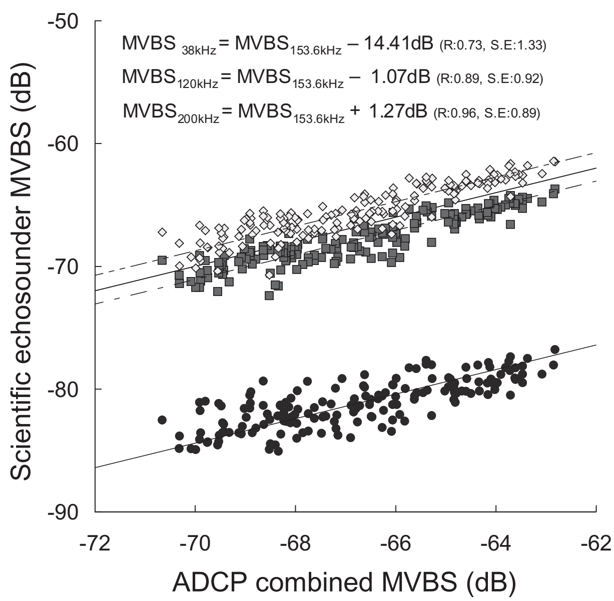

Fig. 8 Scatter plot of combined MVBS measured by ADCP (153.6 kHz) and scientific echo sounder at 38 kHz (●), 120 kHz (■) and 200 kHz (◇) with averaged time by 2 min for extracted euphausiid cells (> –100 dB). SE, standard error.

specifically current velocity, the ADCP has proven to be useful in understanding behavior and biomass density. These approaches should be verified in echo intensity data from the ADCP.

The results show that echo intensity data obtained from the ADCP must be compared and analyzed with backscattering strength data from a well-calibrated scientific echo sounder established on the vessel to supply more varied information and precise measurement of the behavior of the sound scattering layer in use.

ACKNOWLEDGMENTS

We thank the officers and crew of the T/S Ushio Maru, and thank Dr Y Fujimori for net sampling support. We deeply appreciate Dr G Griffiths and Dr H Fuxiang for insightful comments that greatly helped to clarify and refine the paper. This study was partially supported by a Grant from the National Fisheries Research and Development Institute of Korea (RP-2008-FE-001) and the Core University Program on Fisheries Sciences between Japan and Korea.

REFERENCES

1. Plueddemann AJ, Pinkel R. Characterization of the patterns of diel migration using a Doppler sonar. *Deep-Sea Res.* 1989; **36**: 509–530.
2. Luo J, Ortner PB, Forcucci D, Cummings SR. Diel vertical migration of zooplankton and mesopelagic fish in the Arabian Sea. *Deep-Sea Res.* 2000; **47**: 1451–1473.
3. Wade IP, Heywood KJ. Acoustic backscatter observations of zooplankton abundance and behavior and the influence of oceanic fronts in the northeast Atlantic. *Deep-Sea Res.* 2001; **48**: 899–924.
4. Ressler PH. Acoustic backscatter measurements with a 153 kHz ADCP in the northeastern Gulf of Mexico: determination of dominant zooplankton and micronekton scatterers. *Deep-Sea Res.* 2002; **49**: 2035–2051.
5. Demer DA, Barange M, Boyd AJ. Measurements of three-dimensional fish school velocities with an acoustic Doppler current profiler. *Fish. Res.* 2000; **47**: 201–214.
6. Zedel L, Knutsen T, Patro R. Acoustic Doppler current profiler observations of herring movement. *ICES J. Mar. Sci.* 2003; **60**: 846–859.
7. RD Instruments. *Acoustic Doppler Current Profiler, Principles of Operation a Practical Primer*. RD Instruments, San Diego, CA. 1996.
8. MacLennan DN, Simmonds EJ. *Fisheries Acoustics*. Chapman & Hall, London. 1992.
9. Griffiths G, Diaz JI. Comparison of acoustic backscatter measurements from a ship-mounted Acoustic Doppler Current Profiler and an EK 500 scientific echo-sounder. *ICES J. Mar. Sci.* 1996; **53**: 487–491.
10. Deines KL. Backscatter Estimation Using Broadband Acoustic Doppler Current Profiler. *Proceedings of the IEEE Sixth Working Conference on Current Measurement*, IEEE, San Diego, USA, 1999.
11. Francois RE, Garrison GR. Sound absorption based on ocean measurements. Part 2: boric acid contribution and equation for total absorption. *J. Acoust. Soc. Am.* 1982; **72**: 1879–1890.
12. McGehee DE, O'Driscoll RL, Martin Traykovski LV. Effects of orientation on acoustic scattering from Antarctic Krill at 120 kHz. *Deep-Sea Res.* 1998; **45**: 1273–1294.
13. Mikami H, Mukai T, Iida K. measurements of density and sound speed contrasts for estimating krill target strength using theoretical scattering models. *Nippon Suisan Gakkaishi* 2000; **66**: 682–689.
14. Brierley AS, Brandon MA, Watkins JL. An assessment of the utility of an acoustic Doppler current profiler for biomass estimation. *Deep-Sea Res.* 1998; **45**: 1555–1573.
15. Madureira LSP, Everson I, Murphy EJ. Interpretation of acoustic data at two frequencies to discriminate between Antarctic krill (*Euphausia superba* Dana) and other scatterers. *J. Plankton Res.* 1993; **15**: 787–802.
16. Watkins JL, Brierley AS. Verification of the acoustic techniques used to identify Antarctic krill. *ICES J. Mar. Sci.* 2002; **59**: 1326–1336.