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## An assessment of the utility of an acoustic Doppler current profiler for biomass estimation

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### Abstract

Acoustic Doppler current profilers (ADCPs) are being used increasingly to derive estimates of zooplankton and micronekton abundance. The absence of a practical means for users to perform ADCP calibration, however, makes the quantitative value of this approach questionable. In an attempt to evaluate ADCP-derived volume backscattering strength ( $S_v$ ) data, and hence to assess the utility of such measurements for biomass estimation, a regularly calibrated Simrad EK500 scientific echo-sounder (operating at 38, 120 and 200 kHz) and an RDI narrow-band ADCP (153.6 kHz) were similarly configured and run in synchrony on a transect in the Southern Ocean. Data were collected by both instruments from congruent depth (4 m) and time (2 min) bins in order to allow direct comparison of numerous discrete values without the need for further signal averaging. Echoes were recorded from the Antarctic krill, *Euphausia superba*, in deep-ocean and on-shelf locations during day and night. ADCP-derived volume back scattering strength data from shallow, evenly distributed krill targets were well correlated with equivalent data from the EK500 ( $r^2 > 0.98$ ), and the offsets between instruments conformed to those predicted for their respective operating frequencies by a theoretical model of sound scattering by krill ( $H_0$ :  $S_v$  153.6 kHz =  $S_v$  120 kHz + 2.3 dB,  $t_{0.05(2),155} = 1.98$ ,  $t = 0.74$ ,  $P = 0.46$ ). Data from deeper, more irregularly distributed targets differed significantly ( $P < 0.001$ ). We conclude that under some ideal, but probably rare, circumstances data from the ADCP can be used to derive biomass estimates. The numerous uncertainties surrounding ADCP calibration and the current practical impossibility for users to monitor system performance should, however, preclude these instruments from being used as a matter of course to determine abundance estimates, a task that we believe should remain firmly within the domain of a well calibrated scientific echo sounder. © 1998 Elsevier Science Ltd. All rights reserved.

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## 1. Introduction

The acoustic Doppler current profiler (ADCP) is an instrument designed to determine current velocities at multiple depths throughout the water column. It achieves this by emitting short pulses of sound of a known frequency and measuring the frequency of the echo reflected from particles in the water column, which are assumed to be passive tracers of water motion. The change in frequency between the transmitted and reflected sound — the Doppler shift — is dependent upon the motion of the reflecting particles relative to the sound source: particles moving toward the ADCP produce echoes with a higher frequency than that transmitted, whilst sound backscattered from particles moving away from the source has a lower frequency. The faster the relative particle motion, the greater is the magnitude of the Doppler shift. An ADCP has several transducers (typically 4), each producing a single, narrow beam of sound. Each beam has a different but known slanted spatial orientation, and resolving particle velocity components from each of these allows three-dimensional current vectors within specified depth bins to be calculated relative to the ADCP. For vessel-mounted (VM) ADCPs, removal of the ship's motion (speed, direction, pitch, roll and yaw) allows absolute current vectors to be determined. The ADCP is therefore a powerful tool for measuring current velocity whilst underway. Since the mid-1980s ADCP measurements have become an integral component of physical oceanographic studies (Woodward and Appell, 1986), and ADCPs are now widely fitted to research vessels.

In many instances the predominant particles in the water column reflecting sound and causing the detected Doppler shift are planktonic (e.g. Wilson and Firing, 1992). This has led to attempts to use ADCP data to study aspects of the behaviour and distribution of plankton. For example, ADCP vertical velocity measurements have been used to infer rates of zooplankton diel vertical migration (Plueddemann and Pinkel, 1989; Batchelder et al., 1995; Heywood, 1996).

In addition to measuring Doppler shift, ADCPs are also, as a by-product, able to determine the intensity (power per unit area; Urlick, 1983) of received echoes. Some narrow-band ADCPs manufactured by R.D. Instruments (as used in this and the majority of other studies published to date) do so by measuring the magnitude of an *automatic gain control* voltage (AGC) that is automatically supplied to an amplifier with voltage controlled gain. The function of this amplifier is to ensure that all echo signals are processed at a constant power level (R.D. Instruments, 1989), and the amount of amplification required (and hence voltage supplied) is dependent upon detected echo intensity. For a given frequency and intensity of incident sound, echo intensity is a function of the total acoustical backscattering cross section of the particles within the volume of water ensonified (Clay and Medwin, 1977). If these particles are zooplankton, then the magnitude of the returned echo intensity is proportional to zooplankton biomass (Greenlaw, 1979; Foote et al., 1990). This principle underpins the utility of acoustic surveys for quantitative estimation of the abundance of pelagic organisms (MacLennan and Simmonds, 1992) including zooplankton and micronekton (e.g. Brierley and Watkins, 1996; Brierley et al., 1997).

The ability of ADCPs to record variations in echo intensity has been exploited in a number of studies, enabling physical oceanographic data sets to be augmented with information of postulated biological origin collected simultaneously over the same temporal and spatial scales. This approach has allowed putative variations in zooplankton abundance and distribution to be related to variations in prevailing oceanographic conditions (Smith et al., 1989; Roe and Griffiths, 1993). The first studies using ADCP data to measure zooplankton abundance were able to report densities in relative terms only, because it was not possible to determine the intensity of sound pulses transmitted to the water column (Flagg and Smith, 1989; Plueddemann and Pinkel, 1989; Heywood et al., 1991). Variations in echo strength along a single beam could be measured, but intercomparisons between beams or between instruments were not possible (R.D. Instruments, 1990). Redesign of R.D. Instrument ADCP circuitry, coupled with provision of machine-specific factory calibration parameters, however, now enables users to calculate the intensity of the signal transmitted to the water by their instrument, and hence to determine the absolute intensity of the backscattered signal (R.D. Instruments, 1990). More recent studies have subsequently claimed to be able to yield absolute variations in zooplankton abundance (Cochrane et al., 1994; Batchelder et al., 1995; Weeks et al., 1995; Heywood, 1996; Roe et al., 1996).

To date, however, it remains practically impossible for the user to monitor ADCP calibration. Angled beam orientation and the absence of any inbuilt mechanism to assist with the placement of calibration spheres within the narrow ADCP beams effectively precludes the use of standard target calibration techniques commonly used with scientific echo sounders (Foote et al., 1987). Attempts to assess ADCP performance indirectly have, however, been made. Zhou et al. (1994) and Batchelder et al. (1995) fished zooplankton aggregations from which they simultaneously collected ADCP data. They then compared zooplankton densities estimated from net hauls with densities they expected by theory on the basis of ADCP-derived backscattering intensities. At low ADCP backscattering intensities Zhou et al. (1994) found good agreement between observed and expected zooplankton densities, but at high backscattering intensities their predicted zooplankton abundances were 100 times greater than those they observed in nets, a fact that they attributed to net avoidance. Batchelder et al. (1995) suffered difficulties with their net and were able only to compare gross scale integrated ADCP data with zooplankton densities within double oblique water column hauls. As they admit, such comparisons are far from satisfactory because of the tendency of integrated tows to reduce the apparent dynamic range of plankton abundance compared to catches from discrete depth bins. Weeks et al. (1995) have also noted that ADCP estimates tend to portray smoothed zooplankton distributions because of the extended temporal scales over which the data are typically averaged. The net study/ADCP comparisons of neither Zhou et al. (1994) nor Batchelder et al. (1995) were therefore wholly conclusive.

Griffiths and Diaz (1996) addressed the issue of ADCP calibration by comparing volume back scattering strength data from a 153.6 kHz Doppler sonar with data from the 200 kHz channel of a scientific echo sounder. They found a generally good correlation between the two data sets but, in the absence of any information on

the nature of the particles causing the backscattering, or a recent echo sounder calibration, were unable to comment on the significance of the magnitude of the offset between them: for many zooplankton species target strength (dB) for an individual of a given size is not simply a linear function of ensonifying frequency (Chu et al., 1992), and, between taxa, volume back scattering strength at a single frequency is not necessarily a simple function of biomass (Stanton et al., 1994).

It has not yet therefore proved possible to demonstrate conclusively that *in-situ* ADCP backscattering intensity measurements provide a true estimate of zooplankton abundance. In this study we have combined aspects of the two previous approaches to assess quantitatively the magnitude of ADCP derived backscattering intensities. We compare volume backscattering strengths ( $S_v$ ) derived from a narrow-band 153.6 kHz R.D. Instruments VM ADCP with equivalent signals from a Simrad EK500 scientific echo sounder operating at 38, 120 and 200 kHz. This study benefits from the fact that the echo sounder used was calibrated both prior to and immediately after the comparison, allowing its performance to be quantified accurately. In addition, the identity of the scatterers producing the echoes studied was known: they were Antarctic krill, *Euphausia superba* Dana. *E. superba* is one of the best acoustically described micronekton species: its scattering properties have been studied empirically on a number of occasions (e.g. Foote et al., 1990; Hampton, 1992; Everson et al., 1993; Madureira et al., 1993a), and considerable effort has been expended in attempts to model sound scattering by species of similar physical form (e.g. Stanton, 1989; Wiebe et al., 1990; Greene et al., 1991; Stanton et al., 1993a). In addition to simply comparing the magnitude of backscattered signals derived from our ADCP with those observed at different frequencies by our echo sounder, we have been able to compare ADCP backscattering intensities with those predicted for its operating frequency by a validated scattering model. In this way we have drawn upon the best available sources of data to assess the utility of ADCP measurements for determining biomass.

## 2. Materials and methods

Aboard RRS *James Clark Ross* a Simrad EK500 scientific echo sounder is used routinely to conduct acoustic surveys, for example to determine abundance estimates for Antarctic krill *Euphausia superba* (e.g. Brierley and Watkins, 1996; Brierley et al., 1997). The EK500 is currently operated at 38, 120 and 200 kHz, and during the 1995/96 field season, when the present study was undertaken, was configured with software version 4.01 (Simrad, 1993). An R. D. Instruments narrow-band 153.6 kHz acoustic Doppler current profiler is also used to collect underway measurements of current velocity (e.g. Trathan et al., 1997; Brandon et al., in press) and at the time of this study was operating with firmware version 17.07. Both instruments use hull-mounted transducers (approximately 6 m below the sea surface), which are effectively co-located. During a cruise to the Southern Ocean in the vicinity of South Georgia, the EK 500 and ADCP were configured as closely as operational limitations would allow in order to facilitate a direct comparison between data from the two sources.

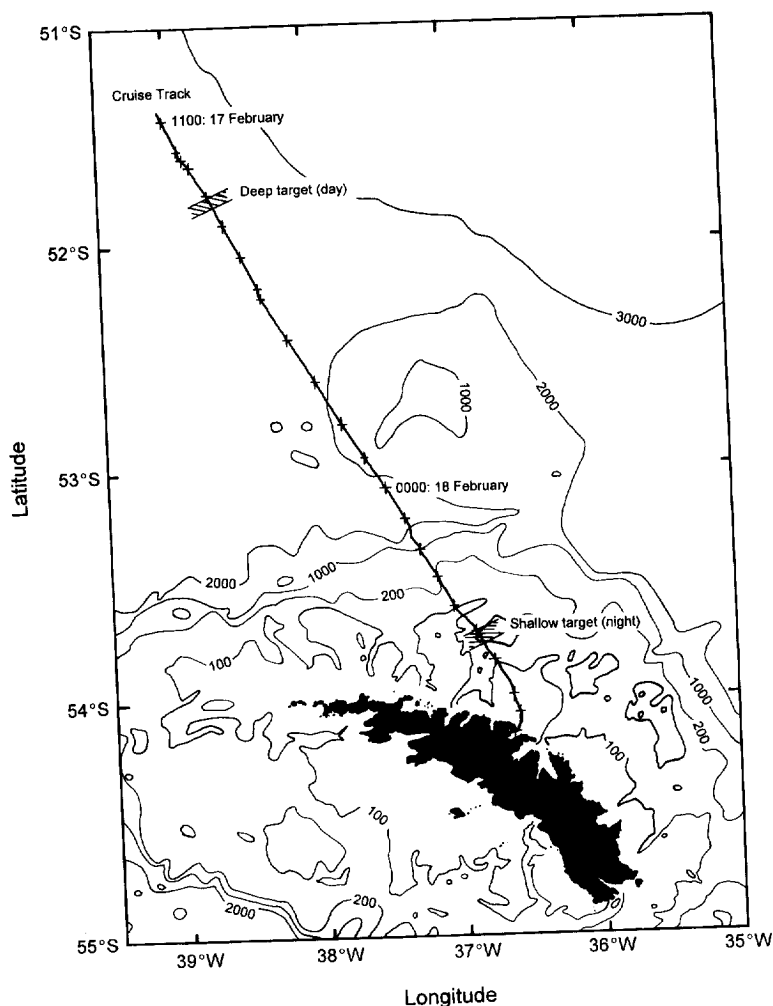


Fig. 1. Map showing the cruise track during the study period, the island of South Georgia and the surrounding bathymetry. The crosses on the cruise track are at hourly intervals, and the hatched areas indicate the positions of the two krill targets (deep and shallow) considered here.

The comparison reported here was undertaken during a 23 h transect between 10:43 GMT (for local time subtract 3 h) on 17 February 1996 and 09:29 on 18 February, incorporating periods of both day and night. The transect ran from an off-shore, deep-ocean location to Stromness Bay on the northern coast of South Georgia (Fig. 1), a site at which our EK500 calibrations are often conducted. The EK500 was calibrated immediately after this comparison between 18 and 19 February, and had previously been calibrated shortly before the study on 16 and 17 January 1996

(38 kHz—number of calibrations = 7, standard error = 0.06 dB; 120 kHz— $n = 6$ , se = 0.04 dB; 200 kHz— $n = 6$ , se = 0.17 dB).

Both the EK500 and ADCP were set to collect data over 4 m depth bins and 2 min time intervals. Within each 2 min period the EK500 transmitted 60 pings (the fastest rate that could be achieved without provoking a *ping interval warning*), whilst the ADCP emitted 96 pings. The EK500 was set with the *noise margin* at zero, and the ADCP was operated with *bottom tracking* off. Our krill biomass surveys are typically concerned with only the top 250 m of the water column because it is predominantly within this range that krill are found, and we were most interested in comparing data over this range. We collected ADCP data to a greater depth than this, however, because calculation of absolute backscatter from ADCP data requires a measure of background noise ( $E_r$ ): it is recommended (R.D. Instruments, 1990; Batchelder et al., 1995; Heywood, 1996) that this be determined by inspection of AGC counts from deep water, where the relative contribution of noise to overall signal intensity is dominant. The ADCP can record data from up to 128 contiguous depth bins, the length of which must be a power of 2 (i.e. 1, 2, 4, 8 m and so on). For each bin the ADCP also reports an indicator of data quality called % good. As the signal to noise ratio in the backscattered signal falls, so the % good also falls, and a commonly used criterion for accepting as valid data for water velocity determination is that % good should exceed 25. Here, with the bin depth set as 1 and 2 m the % good throughout the total depth range was always high, indicating that the data were signal (backscatter) dominated. With the bin length at 4 m the region where % good fell below 25% was reached (generally below 300 m), and below this the signal became noise dominated. Thus we selected 4 m as the bin length for the comparison. Additionally, after transmission of the sound pulse from an ADCP there must be a delay in the time before reception of the backscattered signal can begin to allow for the ringing of the transducers to die down. This delay in time corresponds to a distance from the transducer head from which data cannot be received and is called the *blank beyond transmit*. R.D. Instruments (1990) recommend that this distance be set equivalent to the pulse length, which was 4 m in this case. Given these constraints we had the potential to compare data over the depth range of 12–256 m.

Integrated EK500 data were logged via the ethernet port to a UNIX workstation using custom-written logging software, and time-stamped with reference to the ship's clock. Raw data were subsequently corrected in light of calibration findings, and further edited to remove spurious points, due for example to surface noise or bottom integration in the vicinity of the shelf break. This editing was accomplished using an AVS-based interactive graphical editor (Upton et al., 1989; Socha et al., 1996). Background noise amplified by time-varied-gain (TVG; the function within the scientific echo sounder that compensates for signal loss at depth due to spherical spreading and sound absorption) was also subtracted within this data editor, using an algorithm described by Watkins and Brierley (1996). ADCP data were recorded to PC using the R. D. Instruments data acquisition software D.A.S. (version 2.48). Time stamps associated with ADCP data were corrected for drift in the operating PC's clock, which was monitored throughout the course of the cruise, allowing congruent EK500 and ADCP data to be aligned for comparison.

In order to convert observed ADCP AGC counts into absolute volume backscattering strength values it is necessary to remove that component of the signal due to system noise. R.D. Instruments (1990) suggest that this noise level ( $E_n$ ) be estimated by inspecting data to find the lowest observed AGC values whilst the vessel is stationary (from deep water as described above). It is recommended that noise should not be estimated whilst the vessel is underway because of the additional likelihood of the presence of external noise, for example from the ship or from the flow of water over the transducer head. Part way through the transect reported here we were obliged to stop to secure trawl doors, which had been temporarily stowed outboard. Both acoustic instruments were left running whilst stationary, and AGC count data obtained from the deepest depth bin during this period were taken as representing the noise floor.

Sound speed in both instruments was set to  $1458 \text{ ms}^{-1}$ , a figure derived with reference to CTD profile data collected within the study area (see Brandon et al., in press). Frequency specific absorption coefficients,  $\alpha$ , were calculated from averaged CTD-derived temperature and salinity data, and a pH of 8.0 (as recommended by MacLennan and Simmonds, 1992) according to Francois and Garrison (1982). Values of  $\alpha = 9, 28$  and  $43 \text{ dB km}^{-1}$  respectively were used for the 38, 120 and 200 kHz EK500 data, and  $36 \text{ dB km}^{-1}$  for the ADCP data. Post processing of data from both instruments includes the application of a depth-dependent  $\alpha$  term for derivation of  $S_v$  from measured echo intensity.

ADCP calibration is sensitive to the temperatures of both the transducer and the systems box electronics. Transducer temperature is monitored automatically, and we measured the temperature of the laboratory-based systems box periodically throughout the course of the comparison. The temperature of the ADCP systems box was a constant  $18.7^\circ\text{C}$  throughout the comparison period. Since the RRS *James Clark Ross* commonly works in sea ice, the ADCP transducer is housed in a recessed acoustic well, behind a low density polyethylene window 33.3 mm thick. This prevents ice and freezing damage and has a subsidiary influence of stabilising transducer temperature. Transducer temperature fluctuated only slightly between  $8.2^\circ\text{C}$  and  $10.2^\circ\text{C}$  along the entire length of the transect during which our instruments were configured for this study. XBTs deployed along the length of the transect revealed consistent temperature/depth profiles throughout (Brandon et al., in press). In addition to this broad scale thermal homogeneity, sea surface temperatures remained constant within each of the two specific regions from which measurements discussed here were taken (see Fig. 1). Appropriate temperature values were used for calculation of  $S_v$  from each specific target.

Mean volume backscattering strength,  $S_v$ , was calculated from ADCP AGC counts for each depth/time ensemble according to the procedure given by R. D. Instruments (1990), and with reference to the supplied calibration parameters  $K_{1C}$  and  $K_2$ . The calculation has additionally been described in detail by, for example, Zhou et al. (1994), Batchelder et al. (1995), Griffiths and Diaz (1996) and Heywood (1996) and is consequently not repeated here, other than to say that once completed ADCP data were of an exactly equivalent type to that produced by the EK500 (dB relative to an acoustic cross section of  $1 \text{ m}^{-1}$  (Griffiths and Diaz, 1996)), and hence were directly comparable with data from that source.

Beam averaged processed ADCP data and three frequency EK500 data were loaded into Oracle databases and merged on the basis of time and depth to allow rapid selection of equivalent data points from each source. Unlike previous studies, no bin amalgamation was necessary prior to comparison since both instruments had collected data from exactly equivalent depth-time bins, and hence the original fine scale spatial resolution of all data was preserved.

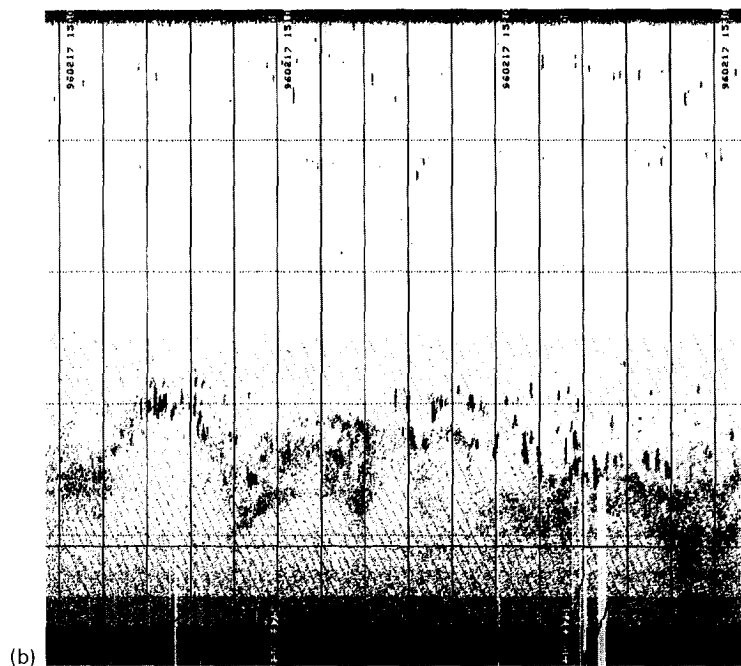
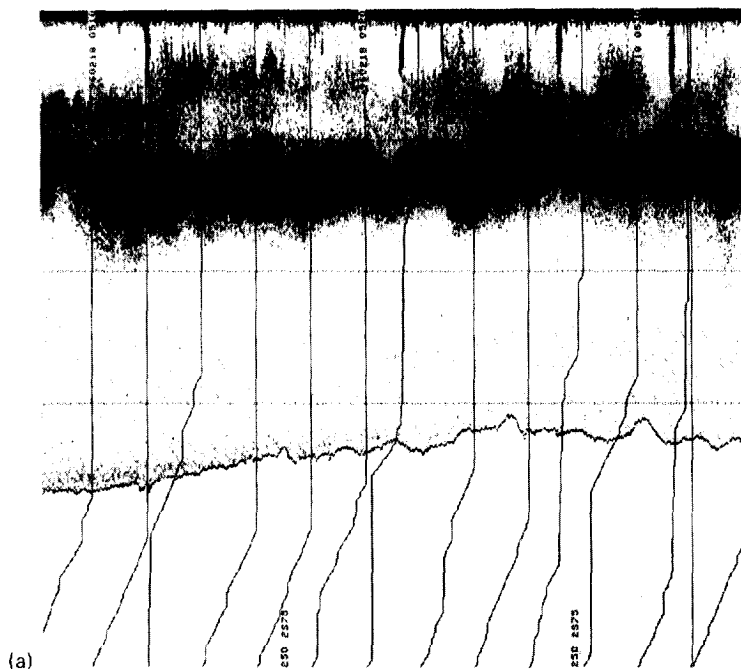
Since it was our intention to assess the utility of ADCP data for biomass estimation, we next inspected the echo charts from the EK500 for the entire transect to find targets with the characteristic appearance of krill (see Fig. 2). In order to verify visual impressions of target identification, EK500 data from the chosen regions were selected from the Oracle data base and analysed within a Mahalanobis distance discriminant analysis procedure (e.g. Manly, 1986) in Minitab (Minitab Inc., 1994). The discriminant analysis had previously been trained with acoustic data gathered around South Georgia during the same field season from numerous biological targets whose identity had been determined from accurately fished net hauls. It has been shown that differences between backscattering signal intensities at 120 and 38 kHz allow Antarctic zooplankton species to be distinguished (Madureira et al., 1993b; Brierley and Watkins, 1996; Watkins and Brierley, 1997), and in an extension of this work using additional data from the 200 kHz channel Brierley et al. (1998) have, in conjunction with the Mahalanobis distance discriminant analysis, been able to distinguish statistically five species, including *Euphausia superba*.

Once target identification had been confirmed, EK500 data and the corresponding ADCP data were selected from the Oracle data base to allow comparisons to be effected. Scatter plots of equivalent data pairs were constructed and regression equations between frequencies calculated. There is an increasing body of evidence suggesting that sound scattering at different frequencies by krill can be modelled as if individuals were finite length, randomly oriented, fluid-filled, bent cylinders (e.g. Stanton, 1989; Wiebe et al., 1990; Chu et al., 1993; Stanton et al., 1993b). To investigate the compliance of our data to this model we first used a two-tailed paired-sample *t* test to compare the observed difference in volume backscattering strength between 120 and 200 kHz EK500 data with that predicted by the model. A *t* test was then employed to assess the significance of the difference in magnitude in signal strength between the EK500 120 kHz signals (the frequency most commonly used for krill biomass estimation) and the equivalent 153.6 kHz signals (the frequency of the ADCP) with those predicted by the model, and hence to assess the quantitative value of ADCP signals as biomass indicators.

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Fig. 2. EK500 120 kHz echo charts showing (a) the highly continuous and evenly distributed shallow water, night time krill target and (b) the dense, discrete krill patches observed off-shelf during the day. Total depth range depicted in each chart is 250 m, and the vertical distance covered by each section of chart is approximately 9 km. Horizontal divisions are at 50 m intervals. Vertical divisions mark the start and end of each 2 min echo integration period: the magnitude of the angled offset in each vertical division provides a relative indication of total detected echo energy (biomass) within that period.





### 3. Results

Krill-like acoustic targets were observed periodically throughout the course of the study transect, most notably in the vicinity of the continental shelf break. During hours of darkness krill were seen more often in the near-surface as extensive, evenly distributed, low-density aggregations; during daylight dense, compact krill swarms tended to occur in deeper water. Despite these temporal differences in distribution characteristics, which follow recognised patterns (e.g. Everson, 1983), in all cases where valid three frequency data were available discriminant analyses (see Brierley et al., 1998) confirmed visual impressions based upon echo chart characteristics that the targets selected for data comparison were krill ( $P > 0.95$ ). None of the targets observed on this particular transect were fished, but extensive fishing in this and neighbouring regions before and after the transect revealed a predominance of small, immature krill with a mean size (AT, Makarov and Denys, 1981) of 31.74 mm (sd = 5.87 mm) based on over 3000 individuals from 26 net hauls. We are therefore confident of the krill population's length frequency distribution at the time this study was conducted.

Inspection of AGC count data from the period when the ship was stationary revealed minimum values of 29 counts below a depth of 422 m. This value was subsequently taken as background noise ( $E_r$ ) and used in conversion of AGC to  $S_v$ . Inspection of data from all other periods (vessel speed constant at  $\approx 10$  knots) revealed identical AGC minima and, in this instance, our noise levels could therefore effectively have been determined in accordance with the method described by Zhou et al. (1994), where background noise was said to be equal to the minimum observed AGC value during the period of interest. Some studies suggest that background noise cannot be measured underway because of the interference of ship's noise and flow noise (R. D. Instruments, 1990; Heywood et al., 1991). Batchelder et al. (1995) have, however, also reported an occasion when there was no significant difference between background noise levels detected underway and those detected whilst stationary.

Heywood (1996) has recommended that certain quality controls be imposed on ADCP data used for derivation of absolute volume backscattering strength. In accordance with her recommendations we had intended to discard all data points where the AGC values were less than 5 counts greater than the noise floor, or the % good value within an ensemble fell below 5%. In actual fact only one depth/time bin exhibited a % good value below 25 (= 23%), and the lowest AGC values were all greater than 10 counts above the noise floor.

Of the many krill targets detected acoustically during the study period, two typical sets of aggregations are described in detail here. One of these was observed at night in a shallow location in the region of the continental shelf-break, the other in deeper water off shelf during daylight (Fig. 1). The shallow water, night time target (Fig. 2a) extended continuously for over 18 km, was distributed from the surface to a depth of approximately 100 m, and had a mean volume backscattering strength at 120 kHz of  $-74.4$  dB, which for krill of the reported length corresponds to a density of approximately 1 individual per  $m^3$ . The selected daylight targets (Fig. 2b) extended over a similar horizontal distance but were located within a depth range between

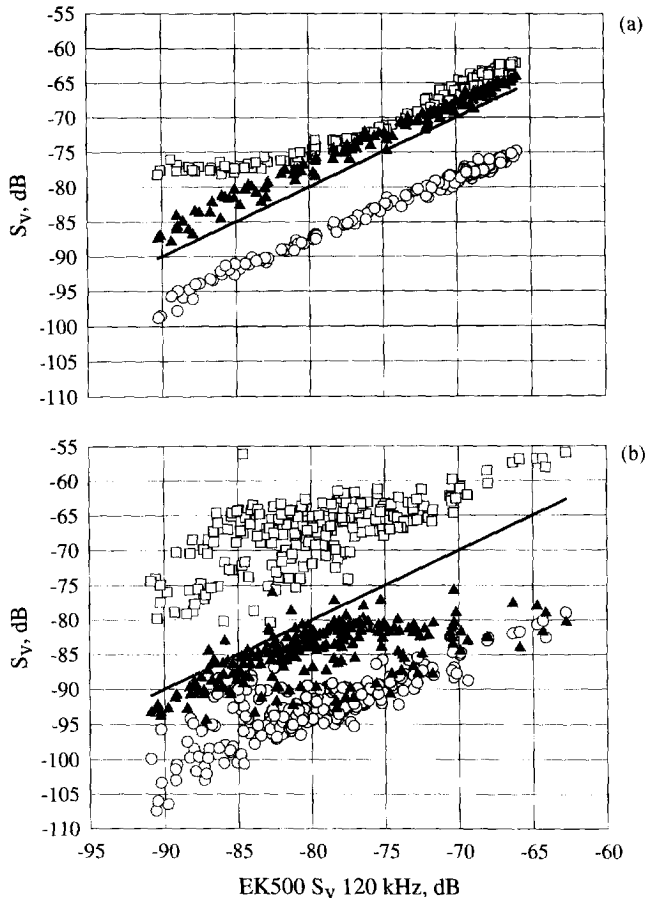


Fig. 3. Scatter plot of 3-frequency EK500 data and ADCP data against EK500 120 kHz data for (a) the shallow-water night-time krill aggregation and (b) the deep-water day-time krill patches. Solid line 120 kHz, (▲) ADCP, (□) 200 kHz, (○) 38 kHz.

approximately 140 and 200 m. Their distribution was in contrast extremely patchy: in some parts densities were high, whereas in others there was no detectable target presence. Detectable volume backscattering strengths from these deep targets spanned more than a 28 dB range (greater than 630 times), with the maximum of  $-62.8$  dB corresponding to a krill density of 16 individuals per  $\text{m}^3$ . The two chosen aggregations fell within a water mass that an XBT section constructed at the same time showed to be thermally homogeneous (Brandon et al., in press).

Fig. 3a is a scatter plot of all acoustic data from the shallow krill aggregation. It shows the three-frequency EK500 data and the ADCP data from this target plotted against equivalent EK500 120 kHz signals. Each point in this figure represents mean volume backscattering strength within a 4 m depth bin during a 2 min ensemble. The

mean % good value for the ADCP data in this figure is 97.0 (sd = 2.4%). Fig. 3a clearly illustrates the generally very close linear relationship between data streams. An exception to this is apparent within the EK500 200 kHz data, where below EK500 120 kHz = -82 dB the 200 kHz data appear to plateau out at -78 dB. This is most likely due to an increasing relative noise contribution to overall 200 kHz signal intensity at low target density (decreasing signal-to-noise ratio). Values of adjusted  $r^2$  between both the EK500 38 kHz and the ADCP data, and the EK500 120 kHz data were >0.98, and once the EK500 200 kHz data had been thresholded at -82 dB then a similar adjusted  $r^2$  value was obtained between this frequency and the EK500 120 kHz data also. Analysis of covariance failed to detect any significant difference between regression coefficients for frequency pairs for any of the acoustic data from the shallow krill aggregation. Fig. 3b is a similarly constructed scatter plot of all acoustic data from the deep water krill aggregations against equivalent EK500 120 kHz data. ADCP data from the deep water targets had a mean % good of 63.4 (sd = 19.0%). The adjusted  $r^2$  value between the deep water EK500 38 and 120 kHz data sets was 0.65. Polynomial regression detected no significant deviation from linearity ( $P = 0.751$ ) in the relationship between these data. In contrast, the adjusted  $r^2$  value between the ADCP and EK500 120 kHz data sets was only 0.38, and quadratic regression indicates that the relationship between these data depart significantly from linearity ( $P < 0.001$ ).

Incorporating size parameters appropriate for krill of the observed population length frequency, and relevant sound speed ( $1458 \text{ m s}^{-1}$ ) and sound speed and density contrast values (Foote, 1990), into the randomly-oriented, fluid-filled, bent cylinder model (in the form given by Stanton et al., 1994), yields an expected difference in volume backscattering strength between 120 and 200 kHz of 3.94 dB. In the absence of 200 kHz data below -82 dB, a two-tailed paired-sample  $t$  test between EK500 120 and 200 kHz signals suggested that, for the shallow krill aggregation, observed volume back scattering strength data did not deviate from this expectation ( $t_{0.05(2),119} = 1.980$ ,  $t = 0.247$ ,  $P = 0.805$ ), and consequently that the model of Stanton et al. (1994) is a reasonable descriptor of sound scattering by the targets ensonified here. The ADCP used here operated at a nominal frequency of 153.6 kHz, and the Stanton et al. (1994) model predicts that the scattering intensity at this frequency will be 2.3 dB stronger than at 120 kHz for krill of the size present. A two-tailed paired-sample  $t$  test between ADCP data and EK500 120 kHz signals also suggested that for the shallow krill aggregation observed volume back scattering strength data complied with this expectation ( $t_{0.05(2),155} = 1.975$ ,  $t = 0.741$ ,  $P = 0.460$ ). A similar comparison between ADCP and EK500 120 kHz volume back scattering strength data from the deep aggregation however revealed highly significant differences between observed and expected values ( $t_{0.05(2),223} = 1.971$ ,  $t = 6.657$ ,  $P < 0.001$ ).

#### 4. Discussion

The role of Antarctic krill *Euphausia superba* is pivotal within the ecology of the Southern Ocean (e.g. Laws, 1984). The species is an important food source for numer-

ous mammalian and avian predators (e.g. Croxall and Prince, 1987; Boyd et al., 1994), and is also targeted by fisheries (e.g. Everson and Goss, 1991). There is consequently much interest in quantifying annual variations in krill abundance (Priddle et al., 1988), both from a stock management and ecosystem monitoring perspective (Brierley et al., 1997). Acoustic survey has for some time been advocated as the favoured technique for assessing krill abundance (BIOMASS, 1977; Everson, 1977). For this reason the acoustic properties of the species have been comparatively well studied (e.g. Everson et al., 1990; Foote et al., 1990; Hewitt and Demer, 1991), since, for acoustic surveys to be of worth, an accurate estimation of the target strength of the species under investigation, the parameter used to convert measured echo intensity into biomass (see MacLennan and Simmonds, 1992), is essential. In addition to empirical measurements of krill target strength, considerable effort has been invested in development of theoretical models to describe sound scattering by krill and other crustacean species of similar physical form (e.g. Greenlaw, 1979; Stanton, 1989; Stanton et al., 1993a, 1994). A body of evidence now exists suggesting that krill scatter sound as if they were randomly oriented, fluid-filled, bent cylinders (e.g. Dalen and Kristensen, 1990; Wiebe et al., 1990; Greene et al., 1991; Chu et al., 1993; Stanton et al., 1993b), and this theory can be used to predict target strengths for krill of known sizes at different echo sounder frequencies. As one of the best acoustically described micronekton species, *Euphausia superba* therefore lends itself well to comparative studies of backscattering at different frequencies, and hence as a medium for *in-situ* assessment of the quantitative value of ADCP volume back scattering strength data for biomass estimation.

Everson et al. (1990) and Foote et al. (1990) have reported a comprehensive investigation of backscattering by caged krill at 38 and 120 kHz. Their study was conducted at Stromness, South Georgia, and considered krill of a similar size range to those observed during the present investigation. This is fortuitous since there is a well documented size-dependent function of backscattering by zooplankton (Greenlaw, 1979; Mitson et al., 1996), and without such congruence a direct comparison of our data with that obtained by Foote et al. (1990) would not be possible. Foote et al. (1990) reported differences in volume backscattering strength between 38 and 120 kHz of between 6.6 and 11.5 dB, which is in very close agreement with the differences observed at those frequencies during the present study for the shallow water target (between 5.6 and 10.1 dB, see Fig. 3a). Chu et al. (1993) have demonstrated that the experimental data obtained by Foote et al. (1990) agree well with values predicted by the randomly oriented, fluid-filled, bent cylinder model (Stanton, 1989), and the similarity between our data and that of Foote et al. (1990) provides the first evidence that our data also comply with the expectations of this model. The present study benefitted from the additional availability of data at 200 kHz and, on a gross scale, the general upward trend of volume backscattering strength with increasing frequency for the shallow water krill aggregation (Fig. 3a) is also consistent with predictions of the model (Stanton et al., 1993). A detailed quantitative comparison of the differences between our 200 and 120 kHz data from the shallow water, night time krill aggregation with the difference obtained by enumerating the randomly oriented, fluid-filled, bent cylinder model (Stanton et al., 1993) in the format given by Stanton et al. (1994) revealed no significant difference, providing additional support for the

applicability of this model as a descriptor of sound scattering by krill. Having established that the model is appropriate over a range of frequencies from 38 to 200 kHz, we believe that use of the same model to assess quantitatively ADCP data (153.6 kHz) by extrapolation from our 120 kHz data is justified. Consequently we used this model to predict from EK500 120 kHz data the expected scattering at 153.6 kHz, the nominal operating frequency of our ADCP, and hence to provide a reference against which to assess the quantitative value of ADCP data.

For the shallow water target a two-tailed paired-sample *t* test failed to detect any significant difference between observed and expected volume backscattering strength differences between the ADCP data and the EK 500 120 kHz data ( $P = 0.46$ ). The failure of data from both instruments to match the expected difference exactly, however, is likely due to a number of factors including sampling error and a lack of absolute data on the physical dimensions of animals causing the backscattering detected in every instance. The deviation may in addition be caused in part by the fact that the ADCP does not ensonify targets from the same angle as does the EK 500. Sound from the EK 500 is projected vertically downwards, whereas each of the ADCP beams is offset at  $30^\circ$  from the vertical. The effect of target orientation, or tilt angle, on target strength has been studied in detail for a number of fish species (see MacLennan and Simmonds, 1992) and has been shown to be considerable. Variation in tilt angle has also been implicated as a factor responsible for observations that differences in backscattering from krill between night and day are greater (by 6.7 dB at 120 kHz) than can be explained by concentration effects alone (Everson, 1982; Everson et al., 1993). The effect of target orientation is likely to be more marked at higher frequencies (such as that used by the ADCP) because of the increased beam directivity pattern (Mitson and Holliday, 1990). As more data become available on the influence of orientation on target strength (e.g. McGehee et al., in press) it may be possible to infer additional information, such as target length, from the difference in signal strength detected at different angles of insonification: at present however the difference in angle of beam orientation of the ADCP and EK 500 serves only to cast uncertainty on the similarity of data from both sources. Despite these and other possible sources of error, however, our data suggest that in the case of shallow, evenly dispersed krill targets the ADCP can provide data for a valid estimation of zooplankton abundance.

Comparison of ADCP and EK 500 120 kHz data from the deep, daytime target aggregations in contrast revealed a highly significant difference between observed and expected signal differences. Indeed the majority of ADCP volume back scattering strength values from the deep krill targets were weaker than those at 120 kHz, an observation completely at odds with theoretical expectations (Stanton et al., 1994). Data at all frequencies from the deep targets are far more scattered than are data from the shallower targets (Fig. 3a, Fig. 3b). 200 kHz signals from the deep targets are consistently higher than predicted. This is most likely a function of the very high noise levels present for this frequency at such depths, and is indicative of the fact that the 200 kHz channel has here exceeded its useful range (Brierley et al., 1998). The 38 kHz data are less well correlated with the 120 kHz data than in the shallow water example, but in all instances the difference between 38 and 120 kHz values fall within the

bounds expected for krill (Madureira et al., 1993a). Possible errors in estimation of attenuation coefficient,  $\alpha$ , are compounded at depth, but we are confident that the values we have used are appropriate: this is supported by the fact that, even in deep water, differences between our 38 and 120 kHz signals continue to be diagnostic, identifying krill correctly (Watkins and Brierley, 1997). We believe that the observed deviation between ADCP and EK500 signals is due primarily to differences in beam geometry between instruments (Griffiths and Diaz, 1996). This results in the ADCP and EK500 sampling different water volumes, an effect that is accentuated with increasing depth. The deep, daytime targets consisted predominantly of irregularly scattered krill aggregations, such that the likelihood of different water volumes at a particular depth containing similar krill densities is further reduced. This is in marked contrast to the situation of the shallow night time aggregation in which targets were evenly distributed throughout a very large 3-dimensional space. Under these circumstances differences in beam geometry have little effect on mean estimates of krill density from a given depth, and the use of beam averaged ADCP data, as here, would serve to further minimise any potential sampling discrepancy. Despite the necessity of using different (but known) calibration constants for different beams, previous studies have been unable to distinguish statistically processed data either between beams (Batchelder et al., 1995) or between correlations between distinct beams and single echo sounder frequencies (Griffiths and Diaz, 1996). This we use to further support our decision to use beam averaged data here.

In situations where known, monospecific acoustic scatterers of a restricted size range are distributed evenly and continuously over an extended (but generally shallow) depth and time range, backscattering values from the ADCP have been shown here to be highly correlated with those from a well-calibrated EK500 scientific echo sounder over a range of backscattering intensities spanning some 25 dB. Differences in signal volume backscattering strength from *Euphausia superba* at 153.6 kHz (the ADCP operating frequency) and the 120 kHz channel of an EK500 scientific echo sounder also comply with those predicted by a validated mathematical model describing sound scattering by euphausiids. In deeper water where the targets are less evenly distributed, both horizontally and vertically, signals from the ADCP are poorly correlated with those from the EK500 and differ significantly from those predicted by the scattering model. In this case, however, there is no *a priori* reason to suggest that estimates from one source are “right” and the other “wrong”. The difference merely highlights the problem of gathering data from erratically distributed targets. Under ideal circumstance, which in practice are likely to be extremely rare, it therefore appears as if the ADCP can be considered as an additional echo sounder channel and as such may provide data from which biomass estimates can be derived. However, given the fact that ADCP beam geometry induces an effective deviation in tilt angle from that at which target strength estimates are commonly made, the acute sensitivity of ADCPs to variations in transducer and electronics temperature, the inability of single frequencies to be used in isolation as diagnostic aids for target identification, and in light of the fact that it remains impossible for the user to routinely verify ADCP performance, we strongly suggest that ADCP data should not be used to derive biomass estimates. Rather we propose that this crucial task, which in some situations could

have severe implications for species management and conservation, be left firmly within the domain of the well-calibrated, multi-frequency scientific echo sounder.

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