BIOACOUSTIC MEASUREMENTS BY USE OF ACOUSTIC DOPPLER CURRENT PROFILER

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Nowadays, each oceanographic vessel is equipped with an Acoustic Doppler Current Profiler. Its task is to determine the value and direction of the vector of water current. It measures the Doppler shift in the frequency of the acoustic wave backscattered by neutrally floating particles suspended in the sea water. A by-product of such measurement is proportional to backscattering strength SV. Starting with the pilot work by Flagg and Smith [3], an ADCP becomes a useful tool for the investigations of the distribution and migration of zooplankton. It enables current and zooplankton abundance to be obtained simultaneously.

The presented paper is an attempt to exploit the data collected in a routine way by the ADCP mounted on r/v 'Oceania' to characterise the biological aggregations, and especially to estimate the distribution of zooplankton and to observe their diel vertical migration.

INTRODUCTION

The specified scientific sonars enable the investigation biological aggregations (scattering layers) by an instantaneous, non-invasive and high-resolution method. Likewise, Acoustic Doppler Current Profiler (ADCP) which is a standard tool for oceanographers, makes it possible to collect the profiles of the backscattering strength along the ship route. The idea has been introduced by Flagg & Smith [3] and Pluddemann & Pinkel [9]. They were deprived of the calibration possibilities, so their estimates were only the relative ones, nevertheless they could compare the inhomogeneities of the spatial distribution of zooplankton biomass. After introducing the calibration constants by the producer the designation of the absolute values of the backscattering strength *SV* occurs to be possible. Then the intercomparison between various devices and, in consequence, various areas and times of observation, can be performed. At the same time the intercalibration with different types of echosounders (e.g. SIMRAD EK500) was performed [5]. Another path of research concerned searching for the relationship between zooplankton distribution and abiotic factors such as temperature, salinity, oxygen, chlorophyll, downwelling irradiance etc. [10, 11]. Also the migration patterns were investigated for various basins and seasons. The researchers focused their attention especially on the vertical migration speed during sunrise and sunset [6, 9].

Diel vertical migration of fish and zooplankton is a widely-known phenomenon, well described in the literature. It takes place in all types of water – from the small lakes to the oceans. Organisms move up and down in a diel cycle, in daylight hours staying in the deep and ascending to the surface in the evening. This kind of animals' motion is connected with the changes in light intensity, but its range and intensity depends also on other hydrological conditions. Usually the migration speed is calculated in two ways: (1) from the shape of the scatterers cloud on the echogram and its slope, (2) directly from the vertical component of the current vector. Generally, the speed values determined from the echogram are higher than the values of the vertical component of water current measured by the Doppler shift.

The main objective of this paper is to recognize the possibility of ADCP to conduct the bioacoustic monitoring of the Baltic Sea. Our specific goals are: (1) to compare values of backscattering strength measured by the ADCP to those obtained by other echosounder; (2) to detect a few cases of diel vertical migration, estimate its range and intensity and calculate its velocity; (3) to compare the computed values of the migration velocity with vertical components of the measured sea current.

1. ADCP OPERATION AND PROCESSING

ADCP works with four acoustic transducers mounted at 90° azimuthal increments, with each beam pointing 20 or 30° off the instrument axis. The four beams record the acoustic signal scattered by the suspended matter (mainly zooplankton), the Doppler shift of its frequency is determined and the velocity vector of the sea current is calculated. It is assumed that the scatterers are neutrally buoyant and their speed is identical with the speed of medium. In order to precisely compute the Doppler shift, the received signal must be amplified to a constant level. The amplification is done by an automatic gain control and its values are stored in separate files as *RSSI* – Received Signal Strength Indicator. This by-product is proportional to backscattering strength *SV*, which is a combination of abundance and backscattering cross-section of scatterers. Depth profiles are created by range-gating the echo signal. The centres of successive range cells (bins) are located on the acoustic axis of the beam in a distance of $(1/2)ct$, where c is the sound speed and t – time from the transmit to the centre of the bin and back. The time gate T_a ensures the spatial resolution along the axis $\Delta R = (1/2)\, cT_a$. Both the values of current vector and *RSSI* are the mean values for the whole bin.

It is impractical to calibrate the ADCP using the standard target method [8], because the four beams are inclined at the angle θ to the vertical and it is impossible to locate the standard sphere within the narrow 4°-beams. In the case of broad band ADCP the *SV* values are calculated from [2]:

$$SV = C + 10 \log ((T_x + 273.16)\, R^2) - L_{DBM} - P_{DBW} + 2\alpha R + K_c (E - E_r) \qquad (1)$$

where:

C – calibration constant,
L_{DBM} – 10 log (T_p), T_p – pulse length [m]),
P_{DBW} – 10 log (transmit power [W]),
T_x - temperature at the transducer [°C],

R – distance transducer-scatterer [m],

α - absorption coefficient [dB/m],

K_c – conversion factor from counts to dB [dB/counts],

E – echo intensity within a bin [counts],

E_r – noise level [counts].

Values of C and P_{DBW} are given by the manufacturer (RD Instruments). E are the values of RSSI in bins. E_r must be found by the user (in practice it is an E value in the last bin, typical value of E_r is 40 counts). T_x are measured and recorded for each transmission, α is calculated according to the appropriate expression [4] on the basis of STD data (salinity, temperature, depth).

2. EXPERIMENTAL RESULTS

In general, we are studying data obtained by the Vessel Mounted Broad Band ADCP operating from r/v "Oceania" at a frequency of 150 kHz. Additional echosounding at a frequency of 30 kHz was performed at the stations for comparison. STD profiling was conducted concurrently in order to give the hydrological background and to determine the coefficient of sound absorption in a sea medium.

At the first step we used some archival data collected by our research vessel "Oceania" during her cruise from the west to the east of the southern Baltic Sea. Fig.1 shows the results recorded by the ADCP in August 2003 along the entire southern Baltic Sea from Arkona to Gdańsk for over 2-days (circa 50 hours). The upper part represents the RSSI counts averaged over the bin size (4m) and time cell (5 minutes = 172 consecutive transmissions). The bottom line found from the threshold criterion $RSSI_{thr}$ = 108 counts is marked. The echo signal in two bins close to this line seems to be strongly dominated by the reflections of different parts of the slant acoustic beams from the bottom. The lower part of Fig.1 demonstrates the chosen fragment spanning the second night from the upper echogram, from 15:00 to 11:00. *RSSI* values – not averaged in time – are recalculated to *SV* values and TVG-corrected. Nocturnal scattering layers can be seen in both echograms, especially at a depth of 20 m during the second night. During the day the scattering layers disappear. An attempt to approximate the shape of scattering patch descending during sunrise by the linear regression line gave the speed of downward vertical movement equal to 0.7 cm/s. This value is similar to those obtained by other researchers in various basins.

The next steps involve the measurements carried out at the chosen stations in order to discern the temporal changes from the spatial ones and to compare the results at two different frequencies. Fig.2 displays two echograms recorded in the morning of the 29th of November 2003 in the Słupsk Furrow by the ELAC echosounder and ADCP together with the temperature and salinity profiles. Thermohaline situation is quite simple: the upper mixed layer of constant temperature and salinity spreads up to the depth of 55 m, below which a warmer and more salty water resides. The left echogram was obtained with a 30 kHz sounding frequency, echo signal envelope was sampled at a frequency of 3 kHz and averaged over 64 consecutive transmissions (~1 minute). The depth resolution of 0.74 m is a result of a pulse length 1 ms. Signals from less than 10 m depth were suppressed, as they were dominated by the dead zone (blanking period) and transducer back lobe reflections from the water surface and ship's hull. The right part represents the *SV* values obtained by ADCP with a 150 kHz frequency, averaged over 4 m bins and 2 minute time intervals. The rectangular bin size is visibly larger than at the left side echogram (4 m times 2 minutes as compared to 0.74 m times 1 minute). The centre of the first bin lies at the depth of 12 m. The left echogram shows the strong scattering layer located at the depth 5 – 20 m, gradually weakening and deepening with

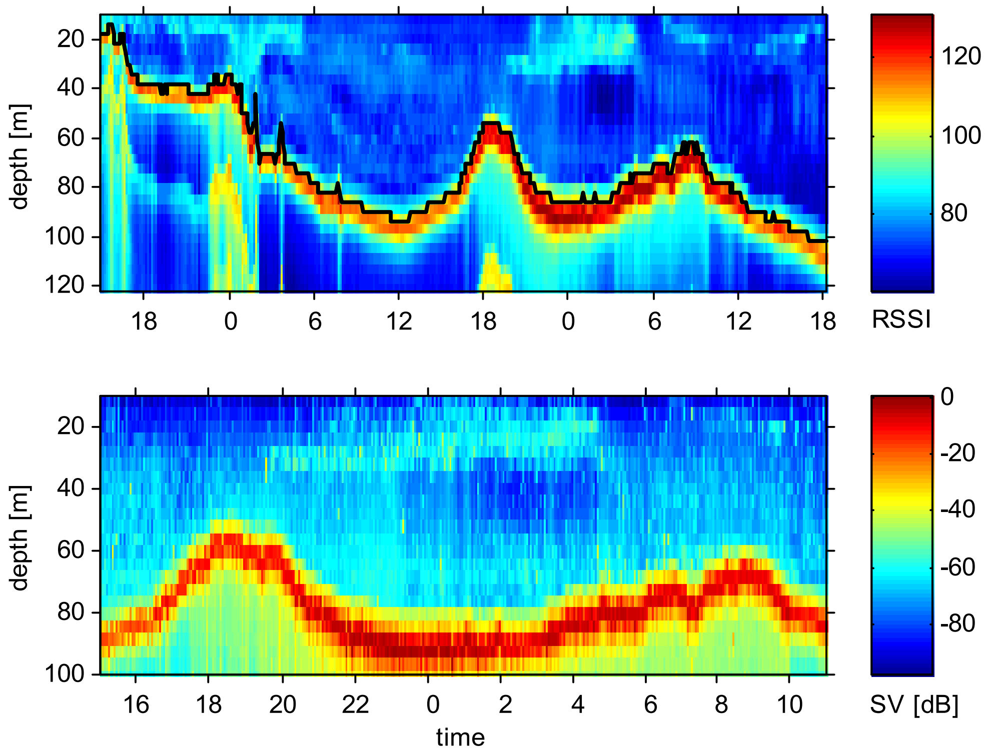

Fig. 1. Raw backscattering data (*RSSI* echogram) obtained by ADCP along the transect Arkona – Gdańsk Deep (15 – 17 August 2003) - upper part - and *SV* echogram for the fragment of this transect (16 August 15:00 – 17 August 11:00) – lower part.

time and disappearing just before sunrise. At ~7 am there arises a thin scattering layer at the depth of halocline (55 m). A different situation was recorded at 150 kHz (the right part of Fig.2) – the scattering layer exists at the depth 30 – 50 m. Its strength and width decreases with time and it disappears about half an hour before sunrise. There is no strong subsurface layer, only in singular bins in this area the value of *SV* exceeds –70 dB. These patches move downwards after sunrise what can be connected with the morning vertical migration. The region of halocline is invisible on the background of near-bottom disturbances. In the next paragraph we are trying to find the explanation for the differences observed in the echograms registered in 30 and 150 kHz.

Fig.3 is analogous to Fig.2, but concerns the series conducted at 6:13 – 8:23 on the 9th of December 2003 in the Gdańsk Deep. This measurement took place just after a 3-day storm of 8-9 degrees in Beaufort wind scale. Very deep thermocline can be seen at the depth of 50 m below the mixed layer with a temperature of 6.3°C. The left echogram reveals the scattering layer at the depth of 20 – 50 m, with a maximum in the vicinity of 50 m. This layer is getting dim and fades away during sunrise, when the halocline layer (~60 m) becomes strong. Characteristic feature of this echogram is the lack of echo at the depth interval 50-60 m, which is the area of thermocline. Similar situation can be seen in the left part of Fig.3. Except for the weaker resolution scale, the scattering layer looks the same, it gradually shrinks and weakens, and becomes invisible just before sunrise. We are not able to conclude of the near-bottom layer for the reasons already mentioned, but there is also no scattering on the thermocline, which can constitute an impassable barrier for the organisms seen by both echosounders.

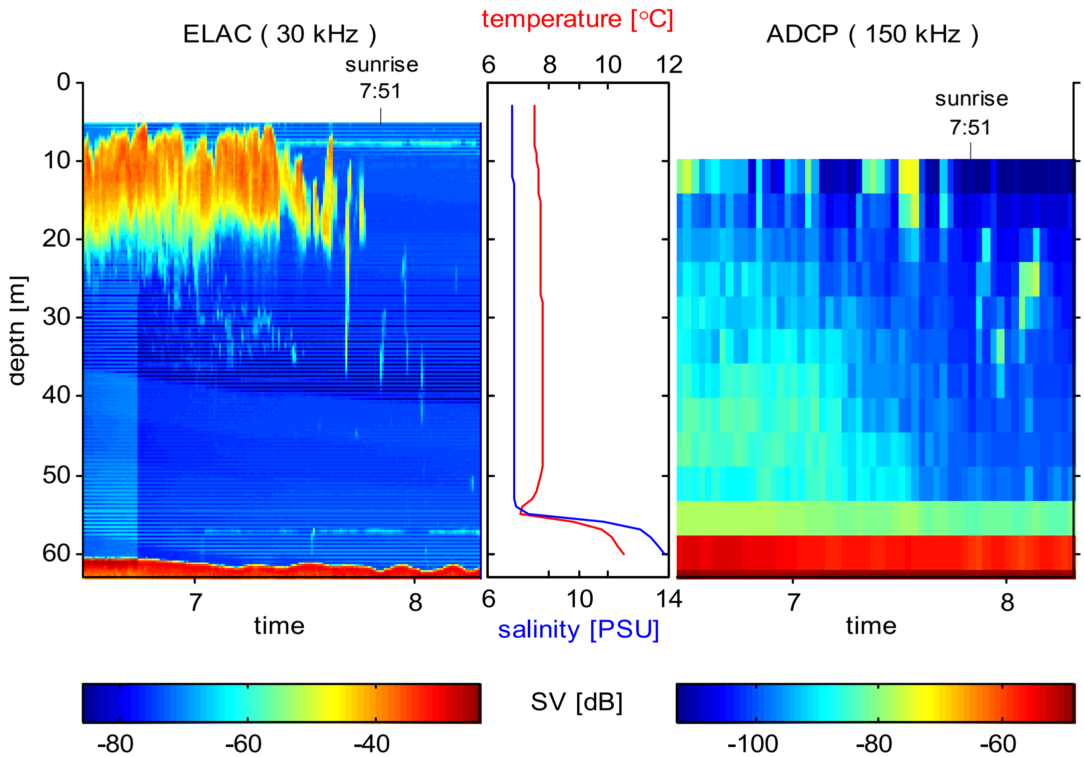

Fig. 2. Two echograms recorded at 30 kHz (left) and 150 kHz (right) and STD profile (middle) for 2 hour series conducted on the 29th November 2003 in the Słupsk Furrow.

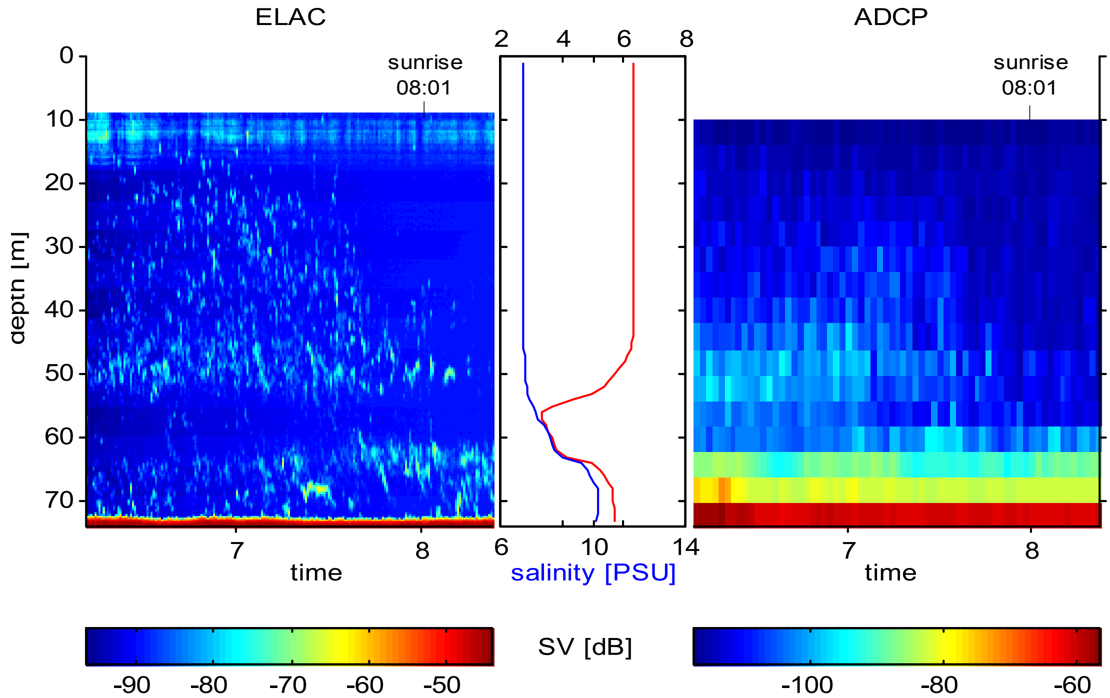

Fig. 3. Two echograms recorded at 30 kHz (left) and 150 kHz (right) and STD profile (middle) for 2 hour series conducted on the 9th December 2003 in the Gdańsk Deep.

In general, ADCP records compared to ELAC ones are characterised by the quicker decay of scatterers in the morning, which can inform about different migration behaviour of smaller organisms (higher frequency) as related to bigger individuals (lower frequency). It seems that the small zooplankton start their downward escape earlier than bigger zooplankton and fish, in all probability due to their strategy of avoiding predators. Another difference is the level of scattering strength *SV* – it is about 20 dB higher at 30 kHz than at 150 kHz. This can be the result of different scattering mechanisms at these frequencies, or, more prosaic, an inappropriate calibration of the equipment.

Unfortunately, an attempt to compare the vertical migration velocity obtained directly from the current measurement and indirectly from the echogram shape has totally failed. The main reason for this occurs to be the lack of the reliable data. The vertical components of current vector present a chaotic set of random values, very often beyond an acceptable interval of velocities possible in the sea. We hope that after installing the special equipment for the correction of pitch, roll and heave of the ship movement the situation will change and errorless measurements of the vertical current component will become possible.

3. THEORETHICALLY BASED EXPLANATION OF DIFFERENCES IN SCATTERING AT DIFFERENT FREQUENCIES

The intensity of sound scattering depends on the relation between the wavelength λ and scatterer size (radius *a* for spherical objects). For scatterers small compared to the wavelength the scattering is weak and increases with the fourth power of increasing frequency (Rayleigh region). For $ka = 2\pi a/\lambda > 1$ scattering is geometrical and does not depend on frequency. $ka = 1$ is the transition value between those two areas of scattering and pertains to the so called transient region, when the scattering cross-section σ_{bs} is changing very quickly and possesses many maxima and minima. In some papers the criterion $ka = 1$ is loosened to $ka = 0.1$. For nonspherical scatterers the term of equivalent sphere is used. It means a sphere of the same volume. For frequency 30 kHz, the radius of equivalent sphere a_{es}, fulfilling the condition $ka_{es}=1$ is equal to 7.7 mm, while for 150 kHz a_{es} = 1.5 mm. In the case of nonresonant scattering the objects "seen" by the lower frequency have to be "seen" by the higher one. It is very easy to compare the scattering cross-section in the Rayleigh region for two frequencies: 30 and 150 kHz. The same particle will scatter $(150/30)^4$ = 625 times more energy at the higher of these two frequencies. It stands for 28 dB difference in target strength $TS = 10\log\sigma_{bs}$. This statement can explain the visibility of scattering layer recorded by ADCP (150 kHz) and invisibility of this layer at lower frequency, but cannot explain the reverse situation observed in Fig.2, when an extremely strong layer is registered at 30 kHz and only much weaker one is registered at 150 kHz. This fact can be interpreted only on the basis of resonant scattering from the gas inclusions, free gas bubbles or fish swimbladders. Gas bubbles are the objects scattering sound waves very strongly compared to all other inhomogeneities of the water column due to their small acoustic impedance related to the surrounding water and due to resonance. Their scattering cross-section at resonance is hundreds times greater than their geometrical cross-section, according to the expression [1]:

$$\sigma_{bs} = \frac{a^2}{\left[\left(f_R/f\right)^2 - 1\right]^2 + \delta^2} \qquad (2)$$

where:

a – bubble radius,

$f_R \sim 1/a$ - resonance frequency,

f – incident sound frequency,

δ - damping constant.

The first hypothesis explaining the reason for the scattering differences was the presence of fish with resonating swimbladders. The model of bubble inside an elastic shell in water worked out by Love [7] was used. It reduces the complicated solution of scattering expression to the same form as the classical free bubble - formula (2) - taking additionally into account the surface tension of the swimbladder membrane and the shear viscosity of fish body. The distortion of the sphere to a prolate spheroid [12] describing the swimbladder shape more realistically was also considered. The spherical swimbladder resonating at a frequency 30 kHz at the depth 15 m has a radius of ~170 μm. Fig.4 presents the frequency dependence of the target strength of a free bubble (expression 2) and swimbladder (Love's model [7]) for the equivalent sphere radius of 170 μm. Frequency shift between the curves is caused by the elongation of the swimbladder and a small flattening of the resonance peak of the swimbladder curve is caused by the fish viscosity. It is clearly seen that in both cases the resonance scattering at 30 kHz is ~25 dB higher than nonresonant scattering at 150 kHz. We assumed that the volume of fish swimbladder stands for 5% of the total fish volume [8] and the fish shape can be approximated by the cylinder with the length to diameter ratio equal to 10. Then

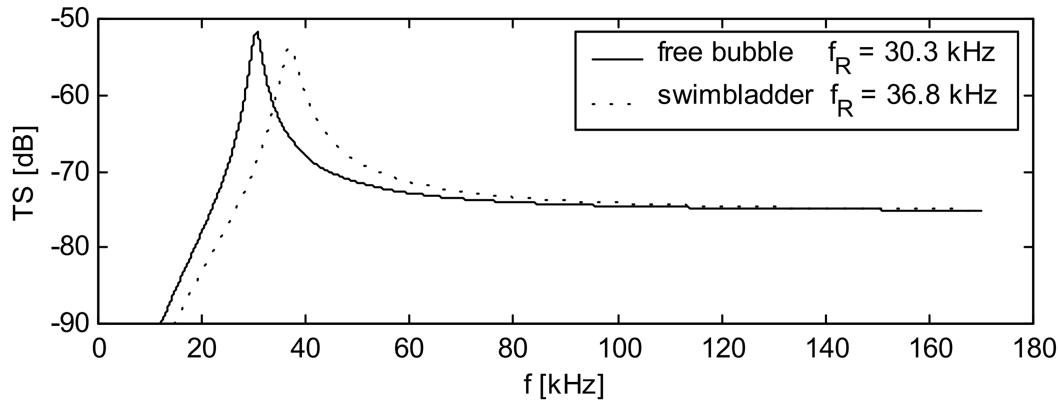

Fig. 4. Target strength versus frequency for free bubble and swimbladder. Equivalent sphere radius a_{es} = 170 μm, shear viscosity coefficient for swimbladder μ = 2 P = 0.2 N/m^2.

the fish length is less than 0.4 cm. Unfortunately, due to our knowledge it seems to be unlikely for such a tiny fish to possess a swimbladder. But it is quite possible that gas bubbles of appropriate size are present in a flesh of jellyfish, abundant in the neighbourhood of the ship during the measurement held on the 29th of November 2003. It can explain the big difference between both echograms in Fig.2.

4. CONCLUSION

Formula (1) and calibration constants delivered by RDI, producer of ADCP, enable the volume backscattering strength *SV* to be computed and the echograms to be retrieved. The spatiotemporal resolution is limited because of averaging over depth bins and time intervals what is necessary to minimalise the error of current determination. There are some ambiguities in concluding about the behaviour of scattering layers and their vertical migration during transects. They are connected with the variability of water mass itself, its hydrology and bathymetry. These problems are reduced when the ship is anchored at the station and the experiment concerns temporal changeability only. The measurements performed at the stations by use of ADCP in comparison to echosounding at a frequency of 30 kHz reveal the visibility of some biological aggregations at one frequency and invisibility at another one. When this invisibility pertains to a smaller frequency, the explanation is easy: organisms are too small to scatter enough long wave sound and they are big enough to interact with short waves. When the scatterers are present at lower frequency and absent (or weak) at higher one, the only reasonable explanation is the resonance of gas bubbles included inside the bodies. Model calculations show that the target strength of a free bubble or swimbladder resonating close to the frequency of 30 kHz exceeds at this frequency the value at 150 kHz by more than 20 dB.

Recorded echograms make it possible to estimate the vertical speed of diel migration at a value of ~1 cm/s.

We would like to emphasise that ADCP gives a possibility of collecting bioacoustic data as a by-product of sea current monitoring. Its main advantage is an ability of concurrent measurement of the physical and biological characteristics of the marine phenomena what enables us to study their interrelation.

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