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ACOUSTICAL ESTIMATION OF THE ANTARCTIC KRILL SWARMS SPATIAL DISTRIBUTION AND BIOMASS

The method of acoustic express-evaluation of the krill (*Euphausia superba* Dana) population spatial structure and determination of its accumulations biomass, with 80 kHz echosounding frequencies has been worked out during the 7-th Ukrainian Antarctic expedition. The method error does not exceed 10 %, which permits to recommend it for usage under the Antarctic krill fishery conditions. The principal possibility to acoustically express-evaluate chorological structure of the Antarctic krill population has been shown. Formation by krill of dense accumulations of different form, elongated for 6 miles, appeared to be an expressed feature of krill behaviour during observations. The school type in krill distribution was observed as well. Parallel to this the accumulations location depth varied in the limits of 10-70 m, and their height made from 5 to 50 m.

Key words: acoustic, Antarctic krill, abundance, biomass

Rather numerous literatures are dedicated to studying the Antarctic krill (*Euphausia superba* Dana) biology taking into consideration trade importance of this species [8, 9, 11]. But its behavior reactions (especially at swarms forming) are investigated insufficiently in spite of some important results, achieved in this field [8]. It was shown, in particular, that krill accumulations at the depth of 180 m have complex spatial structure, depending on localization horizon, vertical gradients of hydrological and hydrophysical parameters, day time, luminosity and other [8].

But as it was shown earlier by us [13, 14, 15], spatial heterogeneity of zooplankton organisms, including krill, is the most important element of the plankton community functioning, determining transformation of the matter and energy on the food chains in the pelagial ecosystem and its productivity. It is hard to overestimate, in particular, actuality of the task of operative and probably more precise assessment of the krill and its biomass accumulations spatial structuredness for fish industry.

The following task was put for participants of the 7-th Ukrainian Antarctic expedition (UAE) from the Institute of Biology of the southern Seas of NAS of Ukraine: to work out method of the express instrumental assessment of krill accumulations spatial structure and biomass in the Sea Scotia and adjacent regions.

Acoustic methods of the biotic pelagial characteristics studying [4, 5, 14], approbated in the number of regions in the World Ocean were applied for the stated task solution in connection with the known limits, which occurs under using the catching tools, used by the classic hydrobiology [6, 12] under studying the spatial structure and temporal changeability of the pelagic communities.

Material and methods. Complex investigations during the 7-th UAE were conducted in the aquatoria with the high biological productivity, which include Bransfield Strait, south parts of the Drake strait and Scotia Sea, and also the north-western part of the Waddell Sea. The main ways of *the krill migration and important industrial* area, which is limited by the Scotia Sea front from the north, Waddell Sea front from the south (fig.1) are situated in this region.

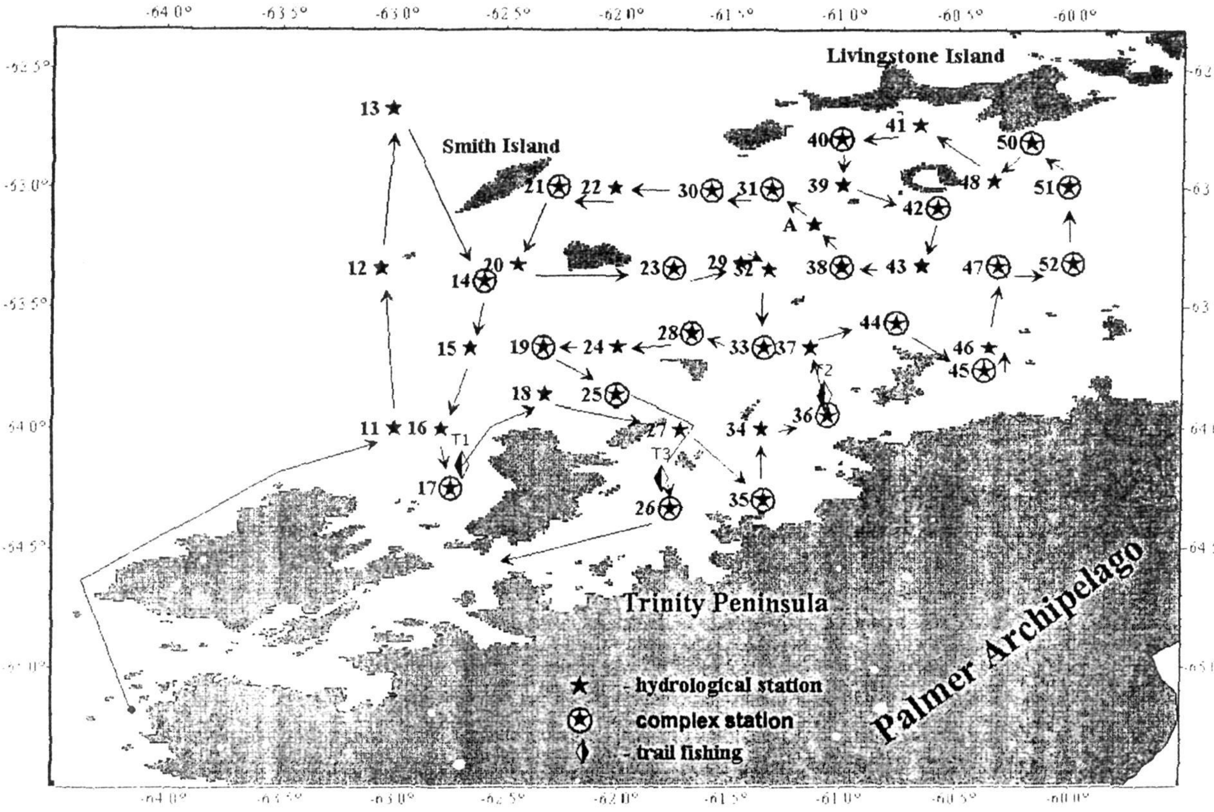

Fig. 1. Stations scheme of hydrobiological investigations carried out in the oceanographic tested area of the Bransfield Strait region

Рис. 1. Схема проведения гидробиологических исследований на станциях океанографического полигона в районе пролива Брансфилд

Investigated region is characterized by the bottom complex topography (presence of many islands, rises and cavities) and hydrological situation (western periphery of the Waddell Sea waters and waters of the Bellinshausen and Scotia Seas junction zone is located in this region), which influence considerably stratification of the hydrological and biological parameters. Western part of the Waddell Sea Front and corresponding currents are formed here and they remove krill juveniles from the shelf regions into the large-scale branches of the Antarctic circumpolar current, which transports krill far to the east in the region of the Southern Orcadian Islands and further to the Southern Georgia [2].

Krill search was realized with the help of hydroacoustic complex "Scat-Plankton", carried out in the IBSS of NAS of Ukraine and intended for the work with hydroacoustic systems of vertical action in the frequency range of 10 - 200 kHz [14]. The tack net for krill accumulations biomass estimation covered all investigated region.

Two «SCAT» complexes of two frequencies realized Echo signals registration:

a) with the help of oscillator of the vessel echosounder with the work frequency 169 kHz and sending period 0.6 seconds. Recording was realized with the averaging of 10 sending, in other words every 6 seconds.

б) with the help of oscillator of the "Plankton – 2" complex, located at the outrigger rot. Work frequency is 80 kHz and sending period is 1 second. Recording was realized with the averaging on 5 sending, in other words every 5 seconds.

Every record was conducted on the straight sections by the tack and distances between stations, fixing current coordinates. Frequencies (169 and 80 kHz), chosen by us for the hydroacoustic researches turned out to be optimal for the works in the Antarctic basin, taking into consideration closeness of the equivalent diameter of the resonance scattering at the frequency of 80 kHz (1.875 cm) to the sizes of the singular scatterers in this region, and also possibility of work with the vessel moving in the range of upper productive layer (0 - 200 m).

Complex "Scat" worked in regime of the program exchange with the ECM in a numerical form and registered echo signals with resolution 1 m at the depth without disturbances under sea force 6-7 and under vessel speed 13 knots with the reflecting the echogram in real and deferred time scales on the color monitor. All the material collected under acoustic measurements turned out to be enough for the stated task fulfillment (table 1).

Three trawl catches (fig.1) by the trawl of Aizeks-Kidd in modification of Samyshev-Mamaev (AKSM) with the enter aperture of 0.6 m^2 length of 18 m, without knot del with the 3 mm cell [10] were conducted for estimating the krill stocks, its size composition, weight range and fatness.

Unfortunately, trawling scheme, used in this cruise under vessel movement in the stern direction did not provide needed exactness of accumulations find out, because the vessel moved backwards with the trawl circling with the diameter of about 50 m. But the unavoidable measurements mistake was minimized thanks to the complexness of the researches carried out.

Table 1. Acoustic measurements materials during the 7-th Antarctic expedition (December 2001 – May 2002)
Табл. 1. Объем материала по акустическим измерениям 7–ой Антарктической экспедиции (декабрь 2001 – май 2002 гг.)

Tested area	Data	Sounds number	Number of the crossed miles with the record COOP3
Testing area in the Bransfield Strait	08.03 -18.03.2002	124516	674
Testing area at the King-George Island	23.03.2002	9572	103
Testing area in the lagoon of the Desepshen Island	21.03 -22.03.2002	6191	-

Results and discussion. Formation of the thick accumulations of the different shape with the 6 miles length was a pronounced feature of the krill behavior in the given observations period. Depth of the accumulations location varied in the limits of 10 – 70 m, and their height – from 5 to 50 m. Different krill behavior was observed sometimes in the night time, when it was situated, the depth to 60 m were registered rarely.

Echogram fragments, obtained under one of trawls of the krill accumulations are presented in the figure 2 (trawl motion trajectory is marked by the line), and the echogram fragment obtained with the help of "SCAT" complex in the night time in the Zherlash strait region and three-dimensional picture of the registered accumulation is presented in the figure 3. Fulfillment of the complex acoustic and hydrobiological surveys permitted to determine spatial structure of krill accumulations precisely enough and to work out algorithms of their biomass evaluation. Matrixes

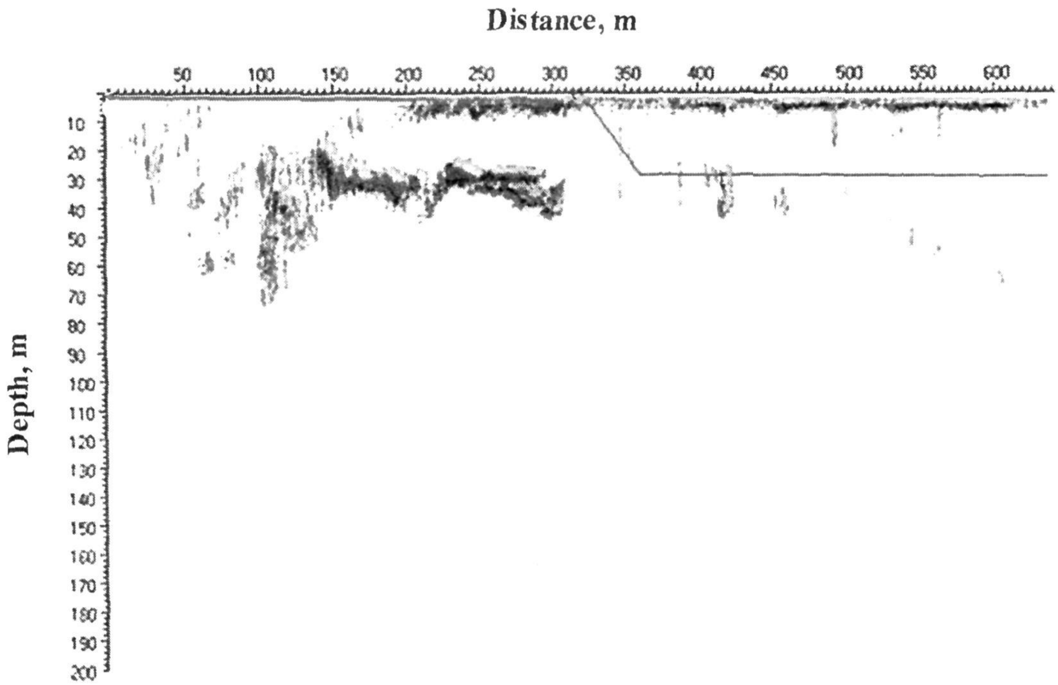

Fig. 2. Echogram fragment of the krill accumulation N2 trawling
Рис. 2. Фрагмент эхограммы траления №2 скоплений криля

of the echogram codes with the calculated intensity values for each 1 m of the layer were the initial data for processing the echo-shooting results.

Correction of the calculated intensity values of the sound volume backscattering strength (SVBS) by the operator was realized for this at the first working stage. It included visual control of the work echograms and excluding the "non-biological" indices sum intensity, in other words other noises and these from the parallel working devices, signals, reflected from the bottom and others, got into the noises integration range. Echo-integrating method, based on the linear dependence between density of the given scatters «ρ» accumulation and sum energy of "M" echo signals from this accumulation, was used for the krill biomass calculation.

Calculated value M for $n_{rec.}$ sendings was reduced to the shooting regime, in other words integral M was calculated for the n_L sendings number for the 1-mile measurements interval. And coordinates, given by the map-plotter GPS were bound to each measurements interval. Codes matrix transformation into Sv - sound volume backscattering strength matrix (SVBS) - was realized according to the results of complex calibrating by the etalon sphere on the formula 1 taking into consideration increase of the layer target strength with the depth because of the increase of the irradiate zone proportionally to the depth square.

Target strength of the sounded volume:

$$TS = S_v V = S_v(\psi R^2 \bullet \frac{c\tau_u}{2}), \qquad (1)$$

where:

TS – target strength of the sounded volume;

S_v – sound volume backscattering strength (SVBS) in 1m^3;

V – sounded volume, m^3;

R - distance to the sounded volume, m;

ψ - corporal angle of the equivalent direction characteristics.

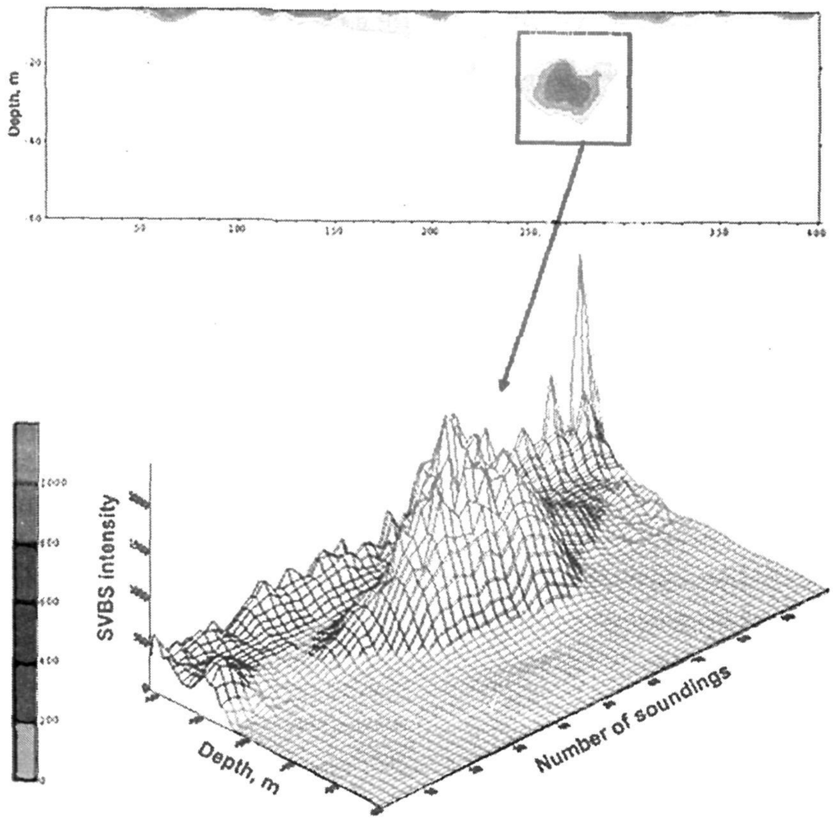

Fig. 3. Krill swarms echogram fragment, recorded by the "SCAT" complex on Ma-rch 19 2002 at the night in the region of Zherlash Strait and its three-dimensional image

Рис. 3. Фрагмент эхограммы, записанной комплексом «СКАТ» 19 марта 2002 г. в ночное время в районе пролива Жерлаш и его 3-х мерное изображение

Signal value at the measurement system outlet under 1 m of sounding volume target strength measurement is equal to:

$$TS = A \bullet N \qquad (2)$$

where:

A – dimensionality (weight) of the information code under the given intensification coefficient, sending duration and band (A are determined at calibrating by the etalon sphere);

N – informational code.

After formulas (1) and (2) transformation we have: $A \cdot N = S_v(\psi R^2 \frac{c\tau_u}{2})$, from which:

$$S_v = \frac{A \cdot N}{\psi R^2 \cdot \frac{c\tau_u}{2}} \qquad (3)$$

Thus, transformation of the codes matrix into the S_v (SVBS) matrix was conducted taking into consideration increase of the sounded volume with the depth because of the increase of the irradiated zone proportionally to the depth quadrate.

The average spatial density in m^3 (P_{avr}, g•m^{-3}) in the 1-meter layer of i-horizon at the "measurements interval" (1 mile) was calculated for to quantitatively evaluate stock of the concrete sound scattering species:

$$P_{avr} = \frac{S_v \cdot W}{TS} \qquad (4)$$

where W – scatter weight;

TS_1 – scatter target strength.

We obtain P_{avr} for each 1-meter layer introduced values obtained in the formula (3) into the formula (4):

$$P_{avr} = \frac{A \cdot \left(\frac{\sum_{h_n}^{h_d} N_c}{n_L}\right) \cdot W}{\psi R_c^2 \cdot \frac{c\tau}{2} \cdot TS} \quad (5)$$

where: ΣN_c – codes sum on *i* horizon after vessel covered 1 mile;

n_L - echosounder sends number for the 1 mile interval.

We obtain P_{avr} value of the *i* horizon of the 1-meter layer in decibels algorithmated expression (5):

$10LgP_{avr} = 10LgA + 10Lg\ (\Sigma N_c/n_L) + 10LgW - 10Lg\Psi - 20LgRc - 10Lg(c\tau/2) - TS_1$ (6)

We get the following expression having joined values, obtained under invariable sending duration:

$K_{dB} = 10LgA - 10Lg\psi - 10Lg(c\tau/2)$ (7)

Then: $10LgP_{avr} = K_{dB} + 10Lg\ (\Sigma N_c/n_l) + 10LgW - 20LgRc - TS$ (8)

$10LogP_{avr}$ values, calculated according to the formula (8) for all horizons (R from 5 to 200 m) were summed up for to determine scatterings average density under the square meter of the water column.

Calibrations of the measuring complex (through channel of the vessel echosounder and device "SCAT") by the etalon copper sphere with the diameter of 30 mm and target strength – 39.7 dB were conducted for to determine dimension of the information code ($10LogA$) under K_{dB} coefficient calculation.

$TS = 10LgA + 10\ LgN,$ (9)

from which:

$10LogA = TS_2 - 10\ LgN,$ (10)

where: TS_2 – target strength of the calibration sphere,

N – code maximal value from the sphere, registered by the "SCAT" complex.

Under reinforcement coefficient of the complex «40» dB *N* = 5850.

In this case we obtain:

$10LgA = -39.7 - 10Lg5850 = -39.7 - 37.67 = -77.37$ dB. (11)

Other K_{dB} components (formula 7) are determined by the technical characteristics of the measuring complex and made:

$10Lg\psi = -13.17$ dB,

$10Lg(c\tau/2) = -4.3$ dB для $\tau = 0.5$ мс.

Then:

$K_{dB} = 10LgA - 10Lg\psi - 10Lg(c\tau/2) = -77.37 + 13.17 + 4.3 = -59.9$ dB

Krill average weight (W) and its sizes were determined by the trawl catches. Table 2 was made up according to the results of the control trawls and krill average length *L* and mass *W* in the trawl samples is pointed in this table.

Table 2. Size-weight characteristics of the caught krill
Табл. 2. Размерно-весовые характеристики пойманного криля

№ trawling	Krill size range, mm	Average size (L), mm	Krill weight range, g	Krill average weight (W), g
№ 1	23 - 26	24.5	0.086 – 0.130	0.108
№ 2	23 - 25	24.0	0.080 – 0.086	0.082
№ 3	22 - 30	26.0	0.07 – 0 130	0 097

Krill target strength (TS) was calculated in coherence with WG-Krill SC-CAMLR [1] recommendations and the krill trawl aiming catch verified results obtained. Krill values 10 lgW and TS are represented in the table 3 depending on its sizes.

The following values were used for to calculate krill biomass in the investigated: average size – 25 mm, average weight – 0.096 g. The target strength (TS) = - 82.7 dB corresponds to the given krill parameters.

The main formula, which takes into consideration these values, can be written as follows:

$10LgP_{avr} = -59.9 + 10Lg\ (\Sigma N_c/n_l) - 40.2 - 20LogRc + 82.7$

Table 3. Values $10\lg W$ and TS under krill different lengths (L)
Табл. 3. Значения $10\lg W$ и TS при разной длине (L) криля

Parameter	Indices values								
L, mm	22	22.6	28.1	35.0	35.3	35.6	36.1	36.3	38.0
TS, dB	-84.53	-84.12	-80.82	-77.50	-77.33	-77.24	-77.0	-76.95	-76.2
10lgW, dB	-11.19	-10.81	-7.79	-4.74	-4.62	-4.50	-4.30	-4.23	-3.56
L, mm	38.3	40	41.9	42.9	45.2	46.7	46.9	47.9	
TS, dB	-76.14	-75.48	-74.78	-74.42	-73.63	-73.13	-73.06	-72.75	
10lgW, dB	-3.49	-2.88	-2.24	-1.91	-1.19	-0.73	-0.67	-0.38	

and after constant values summing up:

$$10\mathrm{Lg}P_{avr} = -17.4 + 10\mathrm{Lg}\ (\Sigma N_c/n_L) - 20\mathrm{Lg}Rc \quad (12)$$

Actual values of the caught krill accumulations density under obtained formula use occurred to be comparable with the calculated values, obtained with the help of the mentioned formula. Discrepancy of the compared values did not exceed 10%.

Plane-table of the tested area with pointing the vessel's route, stations, where hydrobiological measurements were carried out and places of the control trawlings were shown was plotted with the help of the software according to coordinates after the shooting. Calculation of the scatterers density distribution along the whole territory was conducted after calculation of the krill biomass at each measurement interval equal to 1 mile (fig. 4).

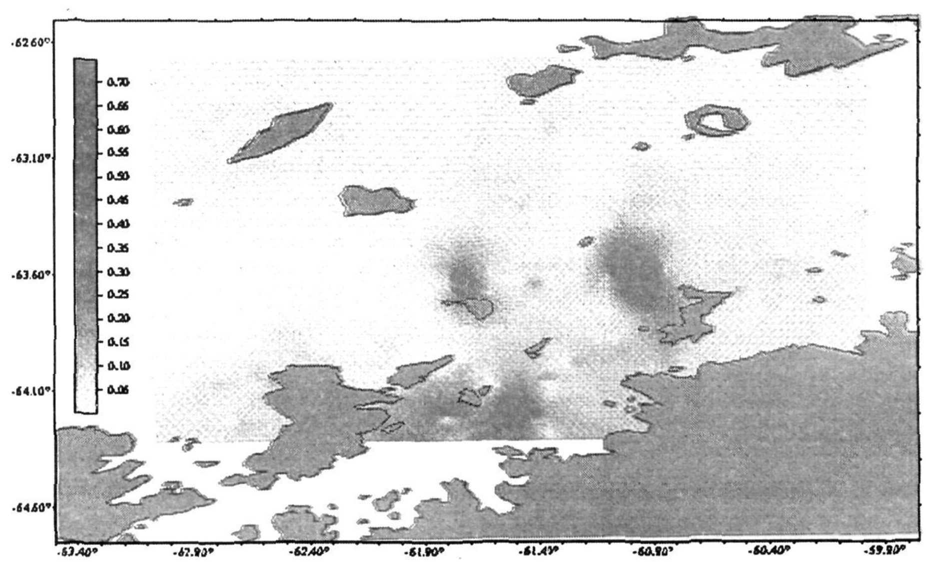

Fig. 4. Krill biomass distribution (kg•m^{-2}) according to the hydroacoustic survey data on the tested area in the region of Bransfield Strait in the period from 08 till 18 March 2002
Рис. 4. Распределение биомассы криля (кг•м$^{-2}$) по данным гидроакустической съёмки на полигоне в районе пролива Брансфилда в период с 08 по 18 марта 2002 г.

Krill accumulations of the industrial importance (kg•m^{-2}) in the Bransfield Strait region can be well seen at the plotted map. As we can see at the figure 4, considerable (industrial) krill accumulations were registered in the south and southeastern tested area parts in the coastal and near islands sections.

Accumulation length is 7.2 miles with the biomass maximum 1.2 kg•m^{-2} at the Snow Island and accumulation length is 15.8 miles with the maximum 1.31 kg•m^{-2} at the Trinity Island (fig. 4). Accumulations at the distance of 11.2 miles with the maximum 0.55 kg•m^{-2} were registered on the spot of trawling № 2 (fig. 1). Krill was registered at the square of 3472 miles^2 from the total square of 7900 miles^2 and its stock made no less than 961500 t with the crayfish average biomass of 75.0 g•m^{-2} according to our calculations.

Krill accumulations of industrial importance were revealed at the King George Island, where unplanned acoustic shooting was carried out (fig. 5).

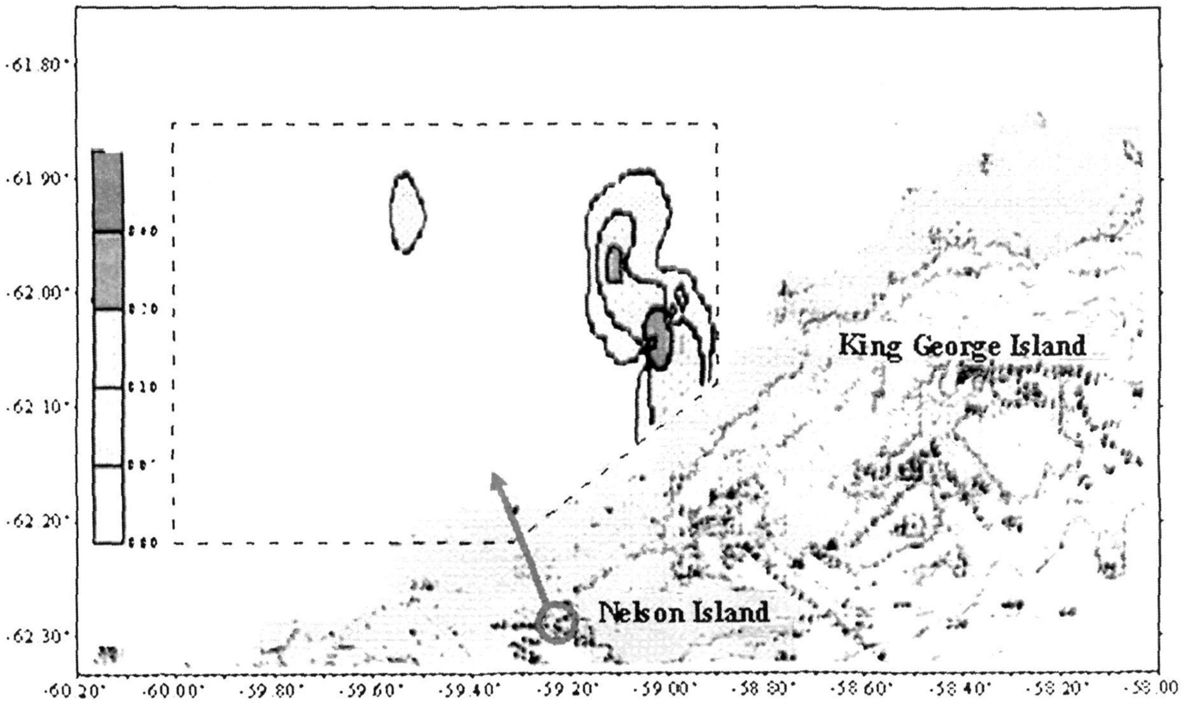

Fig. 5. Krill biomass distribution (kg•m^{-2}) according to the hydroacoustic survey data on the in the King-George Island tested area in March 2002

Рис. 5. Распределение биомассы криля (кг•м$^{-2}$) по данным гидроакустической съёмки на полигоне в районе о. Кинг-Джорж в марте 2002 г.

Krill was registered at the square of 97.9 miles^2 in this region with the tested area square – 685.3 miles^2. Its stock with the average biomass of 116.0 g•m^{-2} in the aggregations of the different type was 39211 t. But about 15 % of the observed square was occupied by krill or in other words 97.9 miles^2.

Total and average stocks of the 2 tested area squares observed, calculated according to the worked out algorithms are pointed in the table 4.

Table 4. Krill biomass calculation results in the investigated regions

Табл. 4. Результаты расчета биомассы криля в районах исследований

Region of investigations	Total stock, t	Average stock at the researched tested area square, t·mile^{-2}
Tested area in the Bransfield Strait	961500	121.7
Tested area at the King-George Island	182565	619.3

As it follows from the represented illustrated material and comparison of the data obtained with the results of numerous acoustic and hydrobiological shootings of other expeditions [3, 4, 5, 7, 9] the worked out algorithms of the acoustic express-estimation of krill distribution along the studied aquatorium and determination of the its accumulations biomass are quite reliable

Conclusions. 1. Principal possibility of the express-assessment of the horological Antarctic krill population structure according to the parameters of the spatial-temporal changeability of the pelagial acoustic characteristic is shown **2.** The dense accumulations forming different shapes with the length of 6 miles was the pronounced feature of the krill behavior in the surveyed period Swarm type of the krill distribution was also observed Depth of accumulations varied in the limits of 10-70 m, and their height made up from 5 to 50 m **3.** Method of the acoustic express-assessment of the krill populations' spatial structure and its accumulations biomass determination was suggested Measurements error does not exceed 10%, and that allows recommending this method for use in the conditions of the Antarctic krill fishery

1. *Anon A* Report of the Tenth meeting of the Scientific Committee for the Conservation of Antarctic Living Resources - SC-CAMLR-X, Australia, 1991 - 29 p
2. *Artamonov Yu V Lomakin P D* Large-scale geostrophyc currents of the Atlantic Antarctica and their annual variation // Ukrainian Antactic Centre Bulletin - 2002 – **4.** – P 32 – 39
3. *Azzazi M Kalinovski J* Spatial and temporal distribution of krill Euphasia superba biomass in the Ross Sea (1989/90, 1994/95) - WG-EMM, Australia, 1997 – 31 p
4. *Everson I Goss C Murray W A* Comparison of krill (*Euphausia superba*) density estimates using 38 and 120 kHz echosounders // Mar Biol - 1993 - **116** P 269 - 275
5. *Green C N Widder E A Youngbluth M J Tamso A Johnson G E* The migration behavior fine structure and bioluminescent activity of krill sound-scattering layers // Limnol Oceanogr - 1992 - V 37 - P 650 - 658
6. *Kils U* The ecoSCOPE and dynIMAGE microscale tools for in situ studies of predator-prey interactions // Archiv fur Hydrob - 1992 - **33** - P 83 - 96
7. *Madureira L S P Ward P Atkinson A* Differences in backscattering strength determined at 120 and 38 kHz for three species of Antarctic macroplankton // Mar Ecol Prog Ser - 1993 - **93.** - P 17 - 24
8. *Pomozov A A* Underwater research of krill aggregations in the Southern part of Scotia Sea // Ukrainian Antactic Centre Bulletin - 2002 – **4** P 125 - 129
9. *Samyshev E Z* Antarctic krill and the structure of planktonic community in its distribution area – Moscow Nauka, 1991 - 168 p
10. *Samyshev E Z* Conclusion about krill population and pelagic ecosystem conditions at the western region Atlantic sector of Antarctic in the pre winter period 1998 // Ukrainian Antactic Centre Bulletin - 2000 – **3** – P 231 - 236
11. *Savych M S* Seasonal and annual variations of the biological state of krill (*Euphausia superba* Dana) in the Southern part of Scottia Sea in 1994 - 1999 // Ukrainian Antactic Centre Bulletin - 2002 **4** – P 117 - 123
12. *Skjoldal H R Wiebe P H Foote K G* Sampling and experimental design – In Zooplankton Methodology Manual - Harris R P Wiebe P H Lenz J , Skjoldal H R , Huntley M -(Eds) - San Diego-Tokyo Academic Press – 2000 - P 33 53
13. *Tokarev Yu N* Biophysical ecology of plankton first results and perspectives of development // Ekologiya morya - 2001 - N 57 - P 51 – 59 (In Russian)
14. *Tokarev Yu N Sokolov B G Vasilenko V I* Use of the biophysical methods in the Antarctic plankton community investigations first results and perspectives // Ukrainian Antactic Centre Bulletin - 2002 – **4** – P 104 - 111
15. *Tokarev Yu N Bityukov E P Vasilenko V I Sokolov B G* Method investigation of the small scale marine plankton communities and their physiological state // Patent N 97091702 of Ukraine, MK И5 AO1 K 61/00 - 13 01 1999

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Акустична оцінка просторового розподілу та біомаси зграй антарктичного крилю. Токарєв Ю. М., Василенко В. І., Жук В. Ф., Соколов Б. Г., Сліпецький Д. Я. У період 7-ї Антарктичної експедиції України розроблений метод акустичної експрес-оцінки просторової структури популяцій крилю (*Euphausia superba* Dana) і визначення біомаси його скупчень при частоті ехолоціювання 80 кГц. Погрішність методу не перевищує 10 %, що дозволяє рекомендувати цей метод для використання в умовах антарктичного промислу крилю. Показано принципову можливість акустичної експрес-оцінки хорологічної структури популяцій антарктичного крилю. Вираженою особливістю поведінки крилю в період спостережень виявилося формування ним щільних скупчень різної форми, довжиною до 6 миль. Спостерігався також зграйовий тип розподілу крилю. Глибина розташування скупчень коливалаçя при цьому у межах 10 – 70 м, а їхня висота становила від 5 до 50 м.

Ключові слова: акустика, антарктичний криль, розподіл, біомаса

Акустическая оценка пространственного распределения и биомассы стай антарктического криля. Токарев Ю. Н., Василенко В. И., Жук В. Ф., Соколов Б. Г., Слипецкий Д. Я. В период 7-й Антарктической экспедиции Украины разработан метод акустической экспресс-оценки пространственной структуры популяций криля (*Euphausia superba* Dana) и определения биомассы его скоплений при частоте эхолоцирования 80 кГц. Погрешность метода не превышает 10 %, что позволяет рекомендовать этот метод для использования в условиях антарктического промысла криля. Показана принципиальная возможность акустической экспресс-оценки хорологической структуры популяций антарктического криля. Выраженной чертой поведения криля в период наблюдений оказалось формирование им плотных скоплений различной формы с протяженностью до 6 миль. Наблюдался также стайный тип распределения криля. Глубина расположения скоплений колебалась при этом в пределах 10 – 70 м, а их высота составляла от 5 до 50 м.

Ключевые слова: акустика, антарктический криль, распределение, биомасса