MIDWATER TRAWL CATCHABILITY IN RELATION TO KRILL AND POSSIBLE WAYS OF ASSESSING GROSS CATCH

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Abstract

Research into midwater trawl catchability rates was carried out on the basis of data obtained from AtlantNIRO expeditions from 1983 to 1990 in the Scotia Sea. A methodology was developed for and applied to determining the rate of krill filtration through the trawl rope and netting and also the probability that krill will come into contact with various parts of the net as it passes through the trawl sides. Studies were based on the results of 250 hauls made with a 72/308 trawl. Catchability was worked out with the aid of fine-meshed chafers, hydroacoustic methods and theoretical calculations. A comparison of the experimental hydroacoustic assessment with the calculated one demonstrated that the theoretical model agreed well with the real situation. Analysis of the efficiency of midwater trawls in the krill fishery indicates that the potential exists for this efficiency to be increased.

Résumé

Une recherche sur les taux de capturabilité des chaluts pélagiques a été effectuée à partir de données provenant de campagnes AtlantNIRO de 1983 à 1990 dans la mer du Scotia. Une méthodologie a été développée puis utilisée pour déterminer le taux de filtration du krill au travers du maillage et la nappe du chalut, ainsi que la probabilité qu'a le krill d'entrer en contact avec les diverses parties du filet lorsqu'il traverse les parties latérales du chalut. Les études reposent sur les résultats de 250 traits effectués par un chalut de type 72/308. La capturabilité a été calculée à l'aide de tabliers de protection à maillage fin, par méthodes hydro-acoustiques et calculs théoriques. Une comparaison de l'évaluation hydro-acoustique expérimentale avec celle provenant de calculs a démontré que le modèle théorique correspond bien à la situation réelle. Une analyse prouve que l'efficacité des chaluts pélagiques dans la pêcherie de krill pourrait être accrue.

Резюме

Исследования уловистости разноглубинных тралов были выполнены по данным экспедиций АтлантНИРО за период 1983-1990 гг. в море Скотия. Была разработана и применена специальная методика определения интенсивности прохождения криля сквозь канатное и сетное полотно, а также вероятность соприкосновения криля с частями сетей при просеивании сквозь стенки трала. В основу работы положены результаты 250 тралений разноглубинным тралом 72/308. Оценка уловистости

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производилась методом мелкоячейных покрытий, гидроакустическим методом и с помощью теоретических расчетов. Сравнение экспериментальной, гидроакустической и расчетной оценок показало хорошее совпадение теоретической модели с практикой. Анализ эффективности разноглубинного трала при облове криля позволяет сделать вывод о том, что имеются значительные резервы для увеличения его уловистости.

Resumen

Se llevaron a cabo investigaciones sobre el coeficiente de capturabilidad de los arrastres pelágicos a partir de los datos de las expediciones de AtlanNIRO realizadas desde 1983 a 1990, en el mar de Scotia. Se desarrolló una metodología para determinar el índice de filtración del krill a través de los cabos y paño de la red, así como la probabilidad de que éste entre en contacto con otras partes de la red cuando entra por los lados de la misma. Los estudios se basaron en los resultados de 250 lances en los que se utilizó un arrastre 72/308. Se pudo calcular la capturabilidad mediante parpallas o protectores de copo de malla fina, métodos hidroacústicos y cálculos teóricos. Al comparar los resultados de la evaluación hidroacústica y de la teórica se vio que el modelo teórico coincidía con la situación real. El análisis sobre la eficacia del arrastre pelágico en la pesca del krill indica que todavía es posible aumentarla.

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1. INTRODUCTION

Krill is an important element in the Antarctic ecosystem. The rational development of the krill fishery hinges on the conservation of the Antarctic marine ecosystem and presupposes extensive scientific research into the habitat area of this crustacean. An integral part of this research includes studying the harmful effects inflicted on the krill habitat area by the fishery and the fishing gear used. Assessing fishing gear catchability rates and gross catch capability are essential components in solving many problems associated with the krill fishery.

The term "gross catch" means the number of individuals of a target species which make up the landed catch as well as those specimens perishing as a result of the impact of fishing gear.

Midwater trawl catchability rates are today being assessed using methods such as fine-meshed chafers (Karpenko, 1983), underwater observation (Zaferman and Serebrov, 1985), hydroacoustics (Berdichevsky, 1985; Kasatkina, 1989) and theoretical model methods (Kadilnikov, 1985). Each of these methods has proven to be inadequate when it comes to solving the task in hand.

The authors of this work have attempted to examine the process of krill fishing and the way the catch is formed in the trawl and also to devise approaches to assessing gross catch by integrating the methods mentioned above.

Yu.V. Zimarev was responsible for developing the methodology and running the calculations to determine the rate at which krill escapes through the trawl ropes and mesh. He also calculated the probability of krill coming into contact with parts of the net as it passed through. Krill distributional characteristics, trawl catchability rates and the methodology for determining the retaining qualities of the trawl were handled by S.M. Kasatkina. Finally, Yu.P. Frolov carried out underwater observations and the assessment on the rate at which krill passed through the trawl mesh using fine-meshed chafers.

2. MATERIALS AND METHODS

2.1 Experimental Hydroacoustic and Theoretical Model Assessments of Trawl Catchability

Data from AtlantNIRO surveys (1983 to 1990) in the Scotia Sea were used in the research on midwater trawl catchability in relation to krill.

It is a well known fact that scientific literature has seen various interpretations of the main parameters in fisheries science. This necessitates that we define the values and terms which will be used throughout this work.

Catchability (**P**) is the probability of taking a catch greater than zero (Kadilnikov, 1985).

The effective fishing area of the trawl over trawling time is that portion of physical space in which there is a likelihood greater than zero that the target species will be caught during the time spent trawling:

$$B = l_r \cdot h_1 \cdot V_t \tau_t, \quad (1)$$

where B - effective fishing area, m^3
l_r - horizontal trawl opening, opening between trawl-boards, metres
V_t - trawling speed, m/s
τ_t - trawling time, seconds
h_1 - vertical effective fishing area of trawl with the condition that
h_1 - h_t when $h_1 < H$
h_1 - H when $h_1 > H$
where h_t - vertical trawl opening, metres
H - depth of water layer where target species is located, metres.

Total catchability (**P**) is the probability that a complex sequence of events will take place. It is expressed as a multiplicative equation in the form of a function of different catchability rates which facilitate the catch process:

$$P = P_r P_{k\text{-}c} \quad (2)$$

where P_r - catchability of the front trawl rigging, i.e., the probability of the target species being caught in the trawl mouth from within the trawl's effective fishing area
$P_{k\text{-}c}$ - catchability of the trawl rope rigging and netting.

Hydroacoustic assessments of a trawl's retaining qualities are based on a comparison of the catch with krill biomass estimates. The latter are obtained from an echo-integrating apparatus in the trawl's effective fishing area and other compartments.

With regard to the second algorithm, the two echo-integrating systems on the vessel made it possible to assess biomass in the trawl's effective fishing area and in the trawl mouth (Kasatkina, 1988). Integration in the mouth of the trawl allows one to assess not only catchability rates, $\mathbf{P} = \mathbf{P_r P_{k\text{-}c}}$, but also the amount of krill being filtered through the trawl rope rigging and netting.

$$K_B = \frac{G}{Q+G} = 1 - \frac{Q}{W_y} \qquad (3)$$

where $\mathbf{K_B}$ - the rate of krill passing through the trawl rope rigging and netting
Q - catch weight in kilograms
G - biomass of krill passing through the trawl rope rigging and netting (kg)
$\mathbf{W_y}$ - krill biomass in the trawl mouth (kg).

By using different numbers of depressor weights on one wing, it was possible to change the vertical opening of the trawl and thereby alter the angle of attack of a section of trawl netting under observation while studying the effects of the trawl's working parameters on the catchability coefficient.

Trawling speed was from 2.5 to 4.5 knots.

The level of escapement through the trawl rope rigging and netting with fine-meshed chafers in place was examined simultaneously with a hydroacoustic assessment of the coefficient $\mathbf{K_B}$.

Experimental assessments of catchability were compared with calculated ones using statistical probability models usually applied to fishing trawls (Methodical Instructions...1985). According to this theory, total trawl catchability and the component parts of this catchability are functions of behavioural and distributional characteristics of the target species and the structural specifications of the trawl itself. Maximum krill speed was taken to be **V** = 0.23 m/s (Kasatkina and Myskov, 1986; Hamner, 1984).

The following parameters describe the behavioural and distributional characteristics of targetted krill aggregations (Kadilnikov *et al.*, 1989):

- distribution of swarm depths;
- linear extent of swarms;
- biometric indicators;
- reaction speed of krill to the moving elements of the trawl;
- density of swarm fields λ_s (number of swarms per unit of water mass area);
- three-dimensional swarm density - β (ratio of swarm volume to habitat area);
- swarm biomass density;
- depth of swarm distribution.

2.2 Modeling the Process of Krill Fishing

In order to determine the rate at which krill pass through the trawl rope and netting, we applied a method used in calculating the distribution of the target species within the trawl during the trawling process (Zimarev, 1985 and 1988). Using a one-dimensional approximation, the following is a system of equations which describes the dynamics of krill numbers per unit volume:

$$\begin{cases} \frac{\sigma p}{\sigma t} + \frac{\sigma y}{\sigma x} = F \\ y = p_s \cdot v_s + p_d v_d \\ p = p_s + p_d \\ p_d v_d = -D \cdot \frac{\sigma p_d}{\sigma x} \\ p_s = p_s \end{cases} \qquad (4)$$

where p - concentration of krill per unit volume (1/m^3)
t - time (seconds)
x - spatial coordinate
y - flow of krill per unit volume (1/m^{2}s)
F - function of krill inflow and outflow
p_s - the number of krill per unit volume which is affected by reotactic ambient factors (1/m^3)
v_s - speed of transport of krill which is affected by rreotactic ambient factors (m/s)
p_d - the number of krill per unit volume which is in a state of agitation (1/m^3)
v_d - speed of incidental runs (m/s)
D - coefficient of krill mobility (m^2/s)
p_s - the probability that krill will respond to reotactic ambient factors.

The function of the inflow and outflow of krill (F) is the sum of two expressions; the first reflecting the amount of krill which passes through the rope sections and trawl netting and the second the herding effect of the trawl.

In order to obtain the single correct solution from the system of equations (4) it is necessary to establish the marginal and initial conditions for p. These conditions are obvious and do not require further explanation. The flow of krill through the front rigging of the trawl is the natural condition for the left edge of the particular area with x = 0. For example,

$$y_{x=0} = pv_t \tag{5}$$

On the right edge, i.e. in the cod line section , with x = L

$$y_{x=L} = 0 \tag{6}$$

where L = trawl length from the zero section to the cod line section under working conditions (metres).

Initial conditions for P are:

$$p_{t=0} = 0 \tag{7}$$

By solving the system of equations (4) numerically using the conditions specified (5 to 7), we find krill distributed along the longitudinal axis of the trawl, P. The integral mass of krill in this particular section of the trawl with the coordinate x and $N_E = [\vec{y}, \vec{s}]\, t$ is the amount of krill which has passed through area (s) of the trawl cover over time (t).

We will assume that krill is not injured each and every time it comes into contact with the net. We are concerned purely with the frequency of krill coming touching the net as it passes through. When assessing the likelihood of krill contacting the net we are invariably confronted by Buffon's "needle" problem. This problem, which has been reduced to two systems of parallel lines, has produced the following expression for determining the probability that krill will come into contact with the net:

$$P_c = \begin{cases} \dfrac{1}{2l} & l_\xi > 2au_1u_2 \\ \dfrac{2l}{\Pi a u_1 u_2}\left(\lambda - \dfrac{e}{2\Pi a u_1 u_2}\right) & l_\xi < 2au_1u_2 \end{cases} \tag{8}$$

where P_c - the probability that krill will come into contact with the net
l_ξ - krill length (metres)
$u_1 u_2$ - net mounting coefficients
l - circumference of krill body (metres)
a - mesh bar

then the number of krill coming into contact with the net is expressed by the equation

$$N_m = P_c N_e \qquad (9)$$

where N_m - the number of krill touching the net
N_e - the number of krill passing through the net.

It should be noted that injuries sustained by krill will not exceed the frequency with which they come into contact with the trawl net.

2.3 Analysis of the Level of Krill Escapement Using Net Chafers; Underwater Observations

Treshchev's methodology (Methodical Instructions...1983) was employed for the collection of data on krill escapement through the trawl. Beginning at the trawl bag and ending at the rope section, fine-meshed chafers were placed on parts of the trawl netting having different sized mesh bars. Visual observations of krill escapement and behaviour in various parts of the trawl were made using a towed underwater device; the Thetis. The fishing process was simultaneously filmed by a videocamera.

3. RESULTS

3.1 Hydroacoustic and Calculated Estimate of Catchability Rate

Research into the catchability of midwater trawls was carried out in the fishing grounds of the Scotia Sea (Sandwich, South Orkney, South Shetland and South Georgia Island areas). The dependency of the trawl's catchability on its working specifications and the distribution of targetted krill concentrations were examined. Krill was taken by several different types of trawl.

Research results are based on the trawl 72/308 whose specifications are listed in Table 2. In the course of the 250 hauls carried out by this trawl, catchability was assessed using hydroacoustic methods.

An assessment of the trawl's catchability in relation to several of its working specifications was made while fishing a concentration having rather homogeneous distributional characteristics. Such a concentration was chosen in order to negate the impact of these characteristics on the assessment.

Results of these assessments, where commercial concentrations are comprised of track-shaped small swarms, are presented below (Kasatkina, 1989). Mean characteristics of krill distribution based on 80 hauls in the Elephant Island area (January, 1985) were as follows:

- mean depth of swarm distribution, **H** (metres) 39
- mean depth of the upper edge of the swarm, $\mathbf{m}_h$ (metres) 21
- mean standard deviation of the depth of the upper edge of the swarm, σ_h (metres) 8
- mean swarm depth, **m (2c)** (metres) 3
- mean standard deviation of swarm depth, σ_{2c} (metres) 1
- mean horizontal extent of swarms, **m** (*l*) (metres) 14

- mean standard deviation of horizontal extent of swarms, σ_l,(metres) 4
- mean swarm diameter (assuming that the swarm is of a cylindrical shape) (metres) 18
- relative three-dimensional swarm density β 0.1211
- three-dimensional density of the swarm field, λ (metres^{-3}) $1.58.15^{-4}$
- two-dimensional density of the swarm field, λ_s (metres^{-2}) $6.19.10^{-3}$

Trawling speed ranged from 2.5 to 4.5 knots; netting angle of attack was between 5° and 9°.

Figure 1 gives the distribution of the catch size per hour trawling while Figure 2 shows the dependency of total catchability (**P**) and the escapement coefficient (**K_B**) of the target species upon the angle of attack (α) and trawling speed (**V_t**). It is clear from Figure 2 that as trawling speed and the angle of attack increase, so does krill escapement. Consequently, total catchability decreases.

At the same time an assessment of krill escapement through the trawl netting was carried out using fine-meshed chafers.The observed dependence of krill escape time on the angle of attack (α) and trawling speed (**V_t**) was in general maintained. It should be noted that in this case the relative escapement coefficient was assessed since the catchability of the chafers themselves is unknown and is taken conditionally to be equal to 1.

Table 2 presents the numerical characteristics of empirical distribution in relation to total catchability (**P**) and its component elements (**P_r, P_{k-c}, K_B**). Hydroacoustic assessment data came from a sample of 80 hauls. The empirical distributions themselves are given in Figure 3.

The biomass density distributions of targetted krill concentrations, which were measured in the trawl's effective fishing area (under the vessel) and in its mouth, are presented in Figure 1 and Table 3. From these illustrations it is clear that concentration density has also been practically unchanged.

An assessment of krill swarm parameters in various regions of the Scotia Sea demonstrated that these swarms evince little response to the vessel and trawl as they pass over them. The distribution patterns of swarm layers and their vertical extent within the trawl's effective fishing area were practically unchanged compared to the same parameters in the trawl mouth.

A hydroacoustic assessment of the 72/308 trawl catchability coefficient, carried out for a wide range of distributional characteristics of targetted krill concentrations and based on data from 250 hauls in various regions of the Scotia Sea, produced the following results. Trawl catchability (**P**) is dependent upon the spatial distribution of krill swarms relative to the effective fishing area of the trawl and, most importantly, on such distributional characteristics as λ_s and β. Catch per hour trawling depends largely on swarm density and to a lesser degree on distributional characteristics (Table 4).

A calculated assessment using models of statistical probability on the theory of fishing trawls was comparatively analysed against a hydroacoustic assessment. Table 5 demonstrates that although the mean values of both empirical and theoretical distributions of catchability coefficients differ, they are reasonably close (Kasatkina, 1988).

Table 6 contains data on the catchability rates of trawls of different design (72/308, 74/416, 76/400) and whose specifications are given in Table 1. Catchability assessment was performed using the calculated method. Keeping in mind the dependency of trawl catchability upon distributional characteristics, the latter were assumed to be the same for each trawl. Parameters of swarm fields in the South Orkney Islands fishing ground in February 1990 were selected as distributional characteristics (Table 7, Figures 4 to 6).

3.2 Analysis of a Process of Krill Passing Through the Trawl Netting

Trawl specifications upon which calculations were based are given in Table 8. A krill swarm with an even spatial distribution, a horizontal extent of 20 000 m, a vertical extent of 200 m and a concentration of 23.25 $1/m^3$, was chosen for the analysis. The mean length of specimens was taken to be 0.043 m and the mass, 0.0044 kg. It was assumed that the maximum body height was 0.018 m and the width, 0.007 m.

Calculations were performed using the theory of differential calculus. An integral interpolation method was used when approximating a differential equation model. The solution to the system of algebraic equations, constructed on the basis of a differential approximation, was achieved using the "run" method.

Implementation of this method meant that at any given moment it was possible to take a large volume of krill in individual sections of netting while allowing krill to pass through these sections and to determine the proportion of krill touching the net.

Table 9 illustrates the filtering capabilities of the netting sections of the three trawls being examined as well as the level of traumatism undergone by krill as they pass through the trawls.

Mean weighted estimates in relation to the 76/400 trawl put the frequency of krill contact with the net at between 26 and 29%. Trawl 74/416 achieved a rate of 9.2 to 13.3% and the 72/308 trawl rated between 20.1 and 27.7%.

The levels of krill escapement determined according to the model in equation (4) were consistent with the results of hydroacoustic assessments and methods using net chafers.

At the same time it should be noted that escapement levels through the rope and broad-meshed sections of the trawl in experimental surveys largely depend upon spatial swarm distribution. Moreover, theoretical calculations do not consider the swarming effect whereby krill enter the trawl as a continuous stream. Therefore the value of absolute escapement in the rope and broad-meshed sections obtained in this manner always exceeds observed levels. In both cases the herding effect of the trawl appears to be absent. It would therefore seem appropriate to use theoretical calculations in accordance with the proposed methodology to solve actual problems.

A more detailed analysis identified areas in the trawl where the greatest instances of contact with the net are likely to occur. Net zone 6 of the 76/400 trawl (see Table 8) which has a mesh bar of 0.04 m and a mounting coefficient of 0.28, is one of these areas. In regard to trawl 74/416, net zones 7 and 8 (mesh bars 1.2 and 0.8 m respectively, mounting - 0.2) are where krill/net contact is the highest. Finally, in trawl 72/308, the relevant net zones are 3, 4 and 5 (mesh bars 1.2, 0.8 and 0.4 m and mounting coefficients of 0.1, 0.147 and 0.159 respectively).

In general, theoretical calculations and actual experiments demonstrate a direct relationship between levels of krill escapement and mesh size, angle of attack and mounting coefficient of the net.

3.3 Underwater Observations, Evaluation of Krill Escapement Using Fine-Meshed Chafers

Visual observations revealed that separate krill swarms have different density. Most swarms consist of small, individual and localised patches with a greater concentration of biomass; the space between these patches is filled by relatively scattered krill.

Observation of krill swarm behaviour indicated the lack of a clearly defined defensive response of krill against the vessel and trawl passing overhead. As the vessel sailed above, the krill swarms remained practically at the same depth and density.

A comparison of the vertical extent of krill swarms in front of the trawl and in its mouth showed that it was virtually unchanged.

Underwater observations of the krill fishing process revealed that krill freely passes through the mesh of the trawl rope section when contact is made. The trawl ropes do not herd krill, i.e. krill escapement reaction is not observed.

A slight concentration of krill occurs when krill is on the outer side of the trawl rope section where small whirlpools are formed by the rope elements.

A quantitative assessment of krill escapement through the trawl rope section showed that the level of this phenomenon depends on the precision with which the mouth section is guided at krill swarms. If the swarm was positioned towards the centre of the trawl mouth, krill did not come into contact with the rope and broad-meshed sections of the trawl and passed into the fine-meshed section. If the trawl is not set accurately, a large part and perhaps even the entire swarm can pass through the rope and broad-mesh sections.

Data on krill retention by fine-meshed chafers indicated that about 15% of swarms trapped in the trawl mouth were in fact passing through the rope section and eventually escaped altogether. The amount of krill which escapes through the last row of rope meshes of the upper panel alone is approximately 1.5 tonnes per haul.

Krill filters just as freely through broad-meshed netting (mesh bar 1 200 to 400 mm) as it does through the trawl rope section.

As the mesh bar decreases towards the codend (i.e., the mesh becomes more compact), a relatively fine, though discernible, layer of water with increased pressure is formed near the trawl netting. This layer of water facilitates the removal of krill and other smaller organisms from the netting. The removal of krill to a certain degree decreases the level of escapement through the mesh. If, however, krill swarm density is high and swarm dimensions exceed the diameter of a particular conical cross-section of the trawl netting, krill are unavoidably squeezed through the mesh.

If we take an example where the targetted krill swarm has a vertical extent of 5 to 8 m and the belly section of the trawl has a cross-section diameter of 5 to 6 m and a mesh bar of 30 mm, then 0.33 kg of krill will escape through one square metre of netting. The amount of krill passing through increases to 1.14 kg when the cross-section diameter is 4 to 5 m and the mesh bar is 20 mm. Finally, when the cross-section diameter decreases to 3 to 4 m and the mesh bar to 18 mm approximately 4 kg of krill, in this case primarily smaller specimens, escapes.

These data indicate that krill filtration in the belly of the trawl is an unavoidable consequence of pressure being applied to smaller specimens.

It is also evident that krill will pass more freely into the trawl bag and the level of escapement will be lower when the angle of the netting into the trawl bag is designed to be less acute.

The efficiency of krill retention in the trawl depends upon the mesh shape used for fine-meshed inserts. A test of trawl bags using fine-meshed inserts, for example, showed that rhomboid-shaped mesh has better retaining qualities than hexagonal. Data on krill filtration through trawl bags having different shaped mesh inserts are presented in Table 10.

4. DISCUSSION

Hydroacoustic investigations demonstrated that total catchability is a random value due to the uniqueness of each haul: the trawling process is different each time as are the behaviour and distribution of the target species. Moreover, catchability $\mathbf{P}_r$ (the probability that the target species will pass from the effective fishing area of the trawl into the trawl mouth) largely depends upon the distributional characteristics of the targetted swarm. The most important of these characteristics are β, λ_s, and the mean standard deviation of the upper edge of the krill swarm (Tables 4, 6, 7, Figures 4 and 5). Trawling speed and the trawl's angle of attack (i.e., the relationship between the trawl mouth parameters and the fine-meshed insert) have a significant influence on the escapement coefficient $\mathbf{K}_B$.

As trawling speed and angle of attack increase, total catchability (**P**) and the catchability of the rope and net sections ($\mathbf{P}_{k-c}$) falls, although the amount of krill filtering through increases considerably (Figure 2, Table 6).

Assessment of targetted swarm parameters in the effective fishing area (in front of the trawl, beneath the vessel) and in the trawl mouth produced the following results:

(a) feable reaction of krill to the vessel and trawl as they passed (depth distribution and vertical extent of krill swarm in the effective fishing area were virtually unchanged compared with the same parameters in the trawl mouth);

(b) limited influence of trawl components such as boards and cables on krill swarms (biomass density in the effective fishing area and in the trawl mouth were practically unchanged) (Table 3); and

(c) underwater observations support the notion that krill have weak defense reactions in relation to abovementioned (b) structural elements of the trawl.

The level of krill damage is also dependent upon these parameters. Nevertheless, further theoretical studies are needed in the area of krill filtration through the trawl mesh. These studies must answer the questions of the relationship between krill damage and the geometrical parameters of the net as well as the biological and mechanical characteristics of the krill body itself, water current speeds and the extent to which the fullness of the trawl bag affects the rate of krill being squeezed through the net.

5. CONCLUSION

After examination of experimental and calculated data, it is possible to make the following conclusions.

Comparison of experimental hydroacoustic and calculated catchability assessments indicates that the theoretical model agrees well with the real situation. Analysis of the efficiency of midwater trawls in relation to the krill fishery demonstrates that there is a good chance that this efficiency can be increased.

Theoretical calculations of the extent of krill filtration through trawl netting and the frequency of contact with the net do not contradict our ideas about the trawling process. In any case, the may serve as a qualitative assessment of the impact of fishing with certain kinds of fishing gear on the gross catch of krill.

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Table 1: Main specifications of midwater krill trawls.

Specifications	Trawl Type		
	72/308 m	74/416 m	76/400 m
Vertical trawl opening at the headline and foot-rope section (metres)	35	40	43
Horizontal and vertical openings of the mouth at the fine-meshed section (metres)	9.8	11.0	17
Horizontal opening between trawl boards (metres)	100	60	70
Horizontal opening between wings (metres)	40	35	37
Trawl length along the belly rope line from the end of the wings to the end of the fine-meshed section (metres)	115	141	138
Length of cable line with tow legs (metres)	150	100	100
Cables - angle of attack (degrees)	11.5	7.2	9.5
Netting in the horizontal plane - angle of attack (degrees)	7.5	4.9	4.2
Netting in the vertical plane - angle of attack (degrees)	6.3	5.9	5.4
Trawling speed (knots)	3.5	3.5	3.5
Length of trawl board rib (metres)	4	4	4
Mesh size (stretched) in trawl bag	6.5	10	12

Table 2: Catchability of the 72/308 trawl in relation to krill - results of a hydroacoustic survey.

Catchability Characteristics	Estimate of Mathematical Expectation	Non-Adjusted Mean Standard Deviation
$\mathbf{P}$	0.0582	0.0231
$\mathbf{P_r}$	0.3052	0.0831
$\mathbf{P_{k-c}}$	0.1907	0.0519
$\mathbf{K_B}$	0.8093	0.2

Table 3: Parameters of density distribution of targetted krill concentrations in the Elephant Island area, January 1985.

Parameter	Density in Effective Fishing Area of the Trawl (p_g, g/m^3)	Density in Trawl Mouth (p_y, g/m^3)	Catch Per Hour of Trawling (**Q/hr**, tonnes)
Estimate of mathematical expectation	7.0	6.6	8.3
Non-adjusted mean standard deviation	9.4	8.5	9.2

Table 4: Correlation of midwater trawl catchability with swarm distribution characteristics.

Swarm Characteristics	Total Catchability	Catch Per Hour of Trawling **Q/hr**
β	0.55	0.54
λ_g	0.65	
p_g	0.05	0.89

Table 5: Experimental and calculated assessments of the catchability coefficient of the 72/308 trawl in relation to krill in commercial fishing grounds.

Catchability	Experimental Assessment		Calculated Assessment		Comment
	Estimate of Mathematical Expectation	Non-Adjusted Mean Standard Variance	Estimate of Mathematical Expectation	Non-Adjusted Mean Standard Variance	
Total catchability (P)	0.0582	0.2231	0.0541	0.0167	Elephant Island January 1985
Total catchability (P)	0.0453	0.0274	0.0567	0.0167	South Orkney Islands December 1984
Total catchability (P)	0.0439	0.0304	0.0489	0.0153	South Orkney Islands January 1985
Total catchability (P)	0.0305	0.0197	0.0389	0.0107	Elephant Island November 1984

Table 6: Catchability coefficient calculated for several types of midwater trawl in relation to krill.

Krill Distributional Characteristics (Table 7)	Trawl Type						Note
	72/308		74/416		76/400		
	P	$\mathbf{K_B}$	**P**	$\mathbf{K_B}$	**P**	$\mathbf{K_B}$	
I	0.0101	0.83	0.0145	0.73	0.0255	0.58	Figure 4
II	0.0181	0.83	0.0424	0.73	0.069	0.58	Figure 5
III	0.0292	0.83	0.0676	0.73	0.1096	0.58	Figure 6

Table 7: Distributional characteristics of krill aggregations in the fishing ground off South Georgia, February 1990.

Numerical Characteristics	Unit of Measurement	Swarm Field I	Swarm Field II	Swarm Field III
Mean depth of swarm distribution, **H**	m	150	200	50
Mean depth of the upper edge of the swarm, $\mathbf{m_h}$	m	109	88	26
Mean standard deviation of the depth of the upper edge of the swarm, σ_h	m	46	30	9
Mean swarm depth, **m** (2c)	m	18	19	18
Mean standard deviation of swarm depth, σ (2c)	m	9	8	3
Mean horizontal extent of swarms, **m** (*l*)	m	88	61	72
Mean standard deviation of horizontal extent of swarms, σ(*l*)	m	18	15	16
Mean swarm diameter **m** (2d)	m	102	78	92
Relative three-dimensional swarm density, β	-	0.022	0.116	0.294
Three-dimensional density of the swarm field, λ	m^{-3}	1.81×10^{-7}	9.18×10^{-7}	2.47×10^{-6}
Two-dimensional density of the swarm field, λ_s	m^{-2}	2.95×10^{-5}	1.83×10^{-4}	1.23×10^{-4}

Table 8: Trawl specifications.

Trawl (m)	Netting Zone Number	Mounting Coefficient	Radius of Trawl Mouth (m)	Fibre Diameter (m)	Mesh Bar (m)	Height of Netting Zone (m)
76/400	1	0.1500	18.80	0.0130	20.000	19.80
	2	0.1500	14.40	0.0130	15.000	14.85
	3	0.1500	11.20	0.0130	6.000	5.91
	4	0.1500	9.80	0.0100	6.000	5.94
	5	0.1500	8.40	0.0100	4.000	3.96
	6	0.2800	7.60	0.0012	0.040	9.60
	7	0.2000	4.75	0.0012	0.030	11.28
	8	0.2600	4.40	0.0012	0.020	13.52
	9	0.2800	3.00	0.0012	0.018	10.5
	10	0.4500	2.50	0.0012	0.012	14.29
	11	0.3000	1.25	0.0011	0.011	23.85
74/416	1	0.1700	19.00	0.0100	8.000	7.88
	2	0.1700	16.00	0.0100	8.000	7.88
	3	0.1700	15.00	0.0100	6.000	5.91
	4	0.1700	14.00	0.0100	6.000	5.91
	5	0.1700	12.00	0.0100	6.000	5.91
	6	0.1700	11.00	0.0100	4.000	3.94
	7	0.2000	10.00	0.0060	1.200	16.50
	8	0.2000	6.00	0.0050	0.800	16.50
	9	0.2500	4.25	0.0012	0.030	10.84
	10	0.2200	3.50	0.0012	0.020	10.40
	11	0.3000	2.75	0.0012	0.018	15.07
	12	0.4500	1.50	0.0012	0.012	15.18
	13	0.3000	1.00	0.0011	0.011	23.85
72/308	1	0.0899	10.78	0.0096	7.000	41.92
	2	0.0631	6.84	0.0096	7.000	6.99
	3	0.1004	6.18	0.0050	1.200	17.91
	4	0.1471	4.56	0.0040	0.800	8.70
	5	0.1594	3.84	0.0610	0.400	8.69
	6	0.1664	3.23	0.0031	0.200	6.11
	7	0.1624	2.88	0.0025	0.020	12.06
	8	0.1830	2.14	0.0022	0.016	29.03
	9	0.2300	0.78	0.0020	0.020	10.58
	10	0.2300	0.49	0.0020	0.012	30.78

Table 9: Krill escapement through and the amount of krill coming into contact with the trawl netting.

Netting Zone	76/400 m			74/416 m			72/308 m		
	Krill Filtered %	Contacted Max %	Contacted Min %	Krill Filtered %	Contacted Max %	Contacted Min %	Krill Filtered %	Contacted Max %	Contacted Min %
1	27.0	1.1	0.4	18.4	2.4	1.0	37	5.1	2.1
2	19.0	1.4	0.6	5.8	2.4	1.0	5.4	7.2	3.0
3	7.8	3.6	1.5	6.1	3.2	1.3	13.6	25.1	10.8
4	7.8	3.6	1.5	11.6	3.2	1.3	5.3	25.8	11.1
5	4.5	5.4	2.2	5.9	3.2	1.3	4.8	44.7	20.1
6	14.0	100	85.6	5.7	4.8	2.0	2.3	74.2	36.6
7	1.4	100	100	23.9	13.3	5.6	2.6	100	100
8	5.7	100	100	9.5	19.6	8.3	5.3	100	100
9	1.7	100	100	2.9	100	100	0.8	100	100
10	1.2	100	100	0.7	100	100	2.4	100	100
11	0.7	100	100	1.2	100	100			
12				0.5	100	100			
13				0.4	100	100			

Note: The level of krill escapement is determined in relation to the amount of krill caught while the number coming into contact with the net is determined in relation to the amount of krill filtered through the net panel.

Table 10: Specific krill escapement.

Shape of mesh inserts	Average value of krill escapement through the trawl bag, kg/m²		
Rhomboid	a=100 (30) mm 0.2	a=80 (20) mm 0.2	a=60 (18) mm 0.2
Hexagonal	a=100 (20) mm 0.2	a=80 (14) mm 0.3	a=60 (11) mm 0.8

Note: Mesh bar of fine-meshed inserts is given in brackets; "a" is the mesh bar of the trawl.

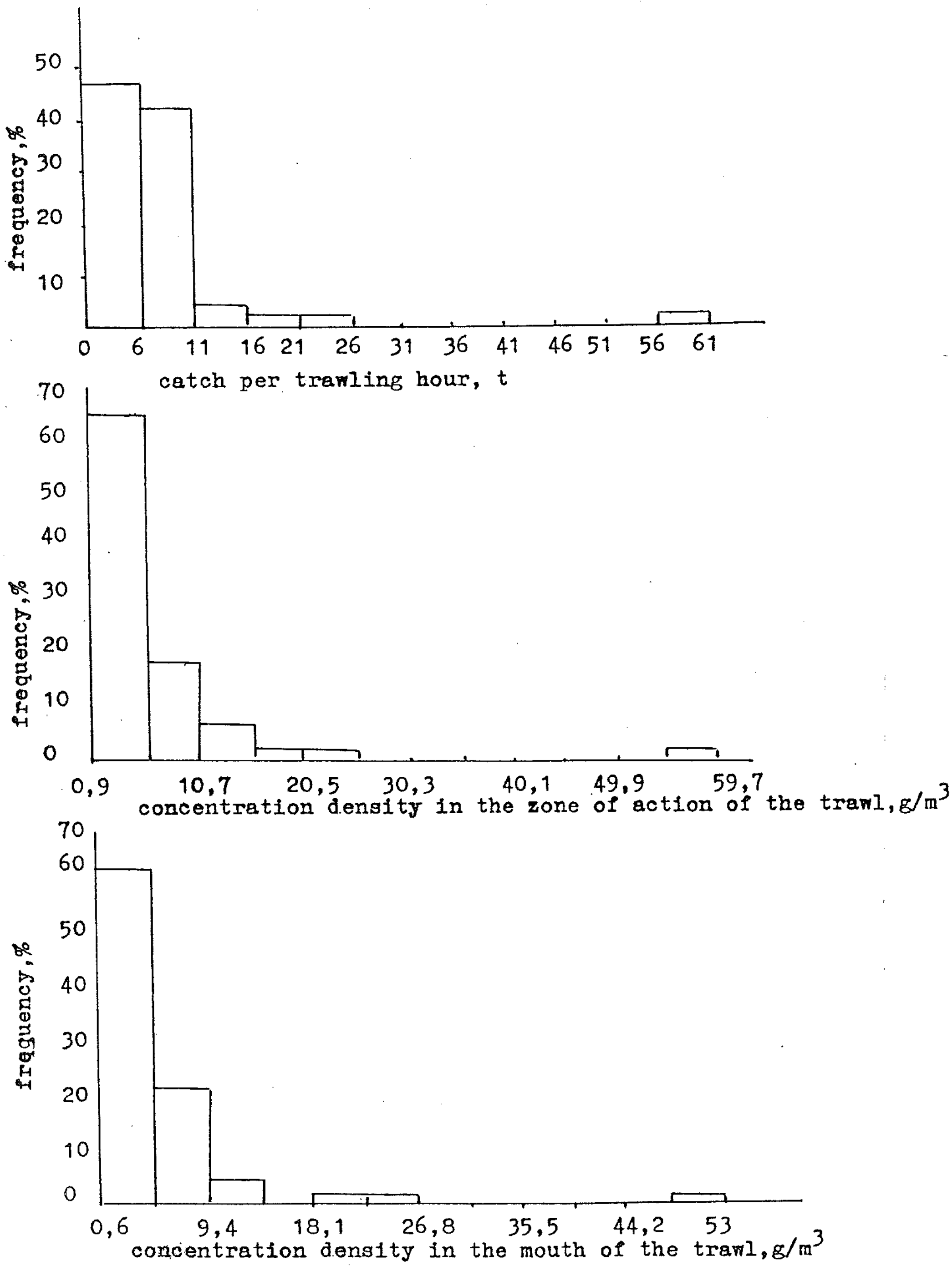

Figure 1: Density distribution of targetted krill aggregations and catch per hour of trawling during the hydroacoustic assessment of the catchability rate of the 72/308 trawl.

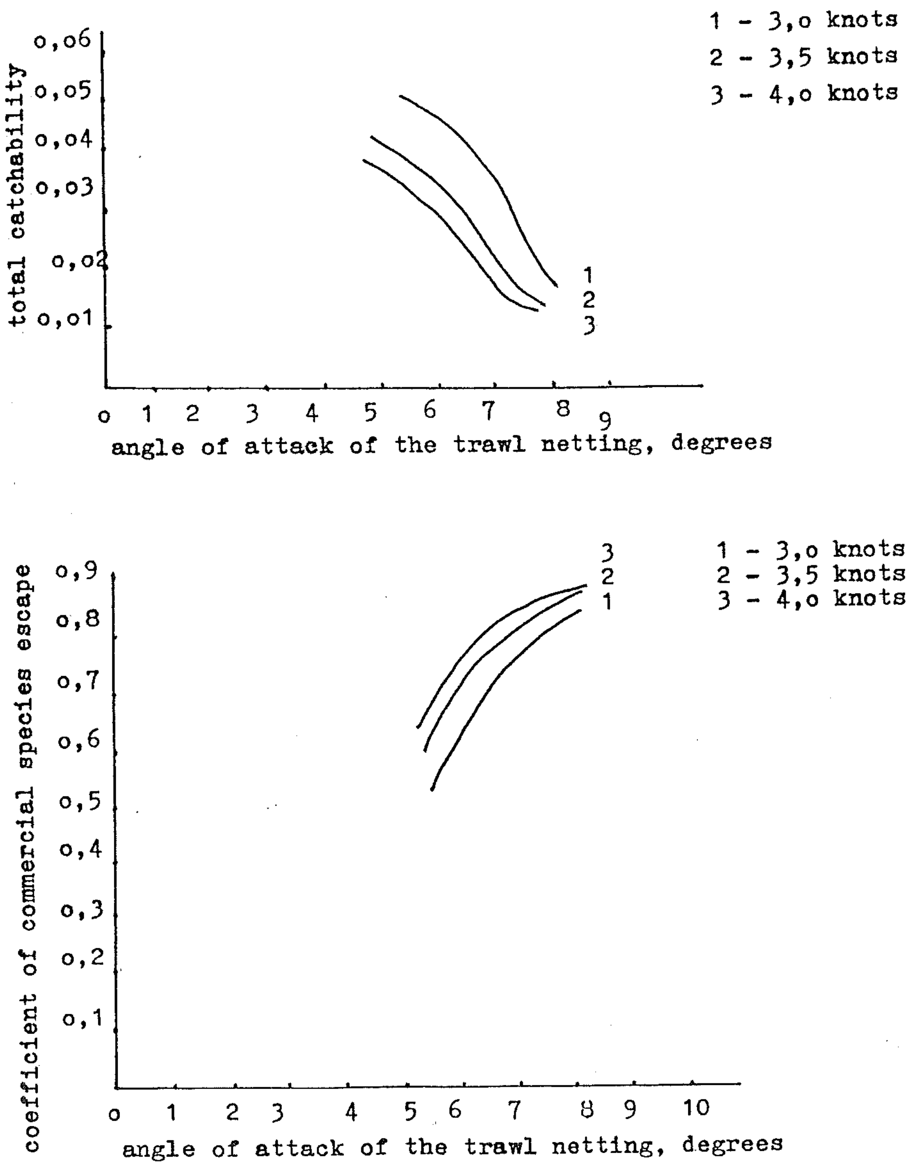

Figure 2: Relationship between total catchability of the 72/308 trawl, trawling speed and netting angle of attack according to hydroacoustic data.

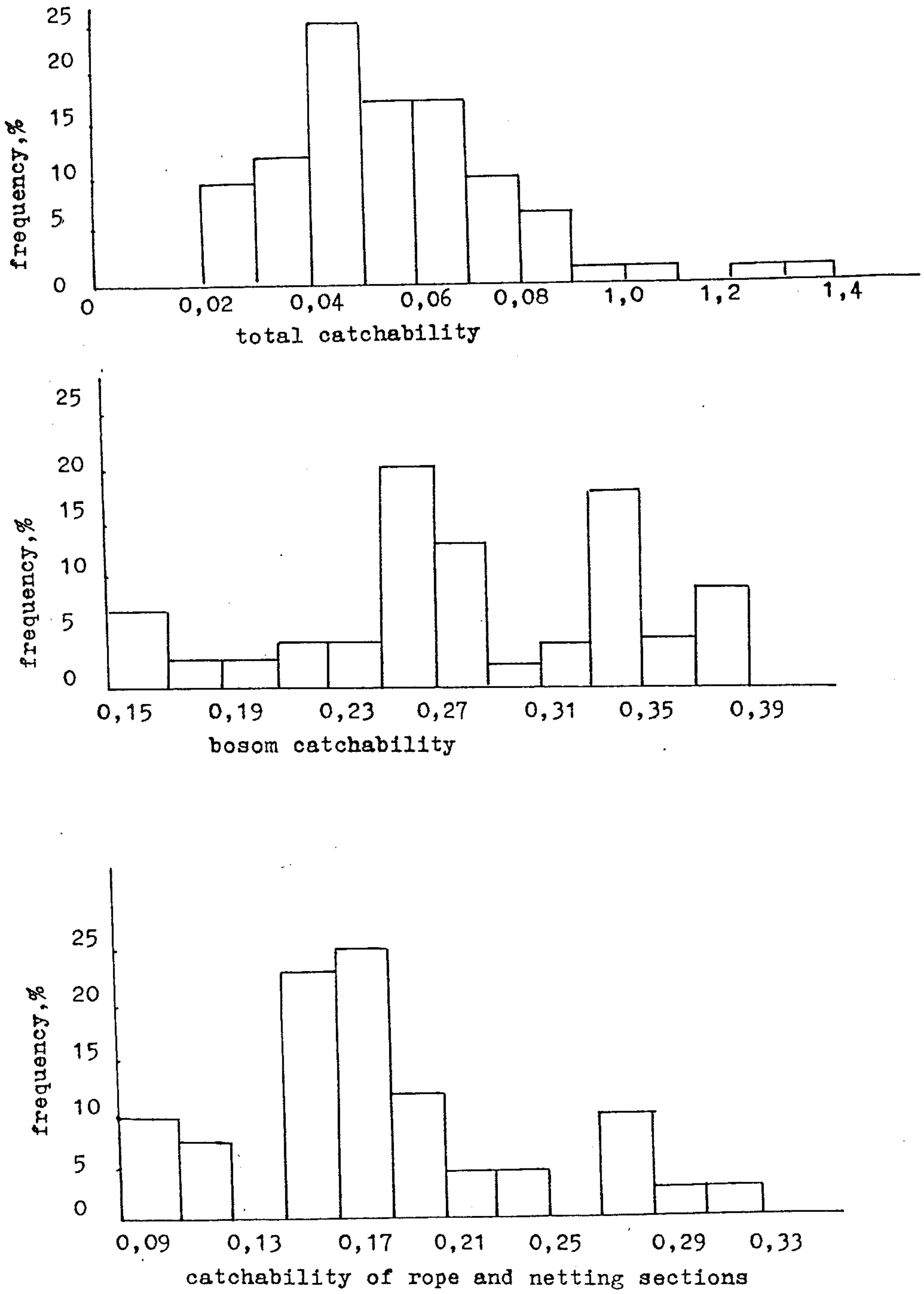

Figure 3: Histograms of distribution in relation to the catchability rate of the 72/308 trawl from targetted krill concentrations in the Elephant Island area in January 1985. (Hydroacoustic data).

Figure 4: Echogram of krill swarms in the Coronation Island fishing ground, February 1990.

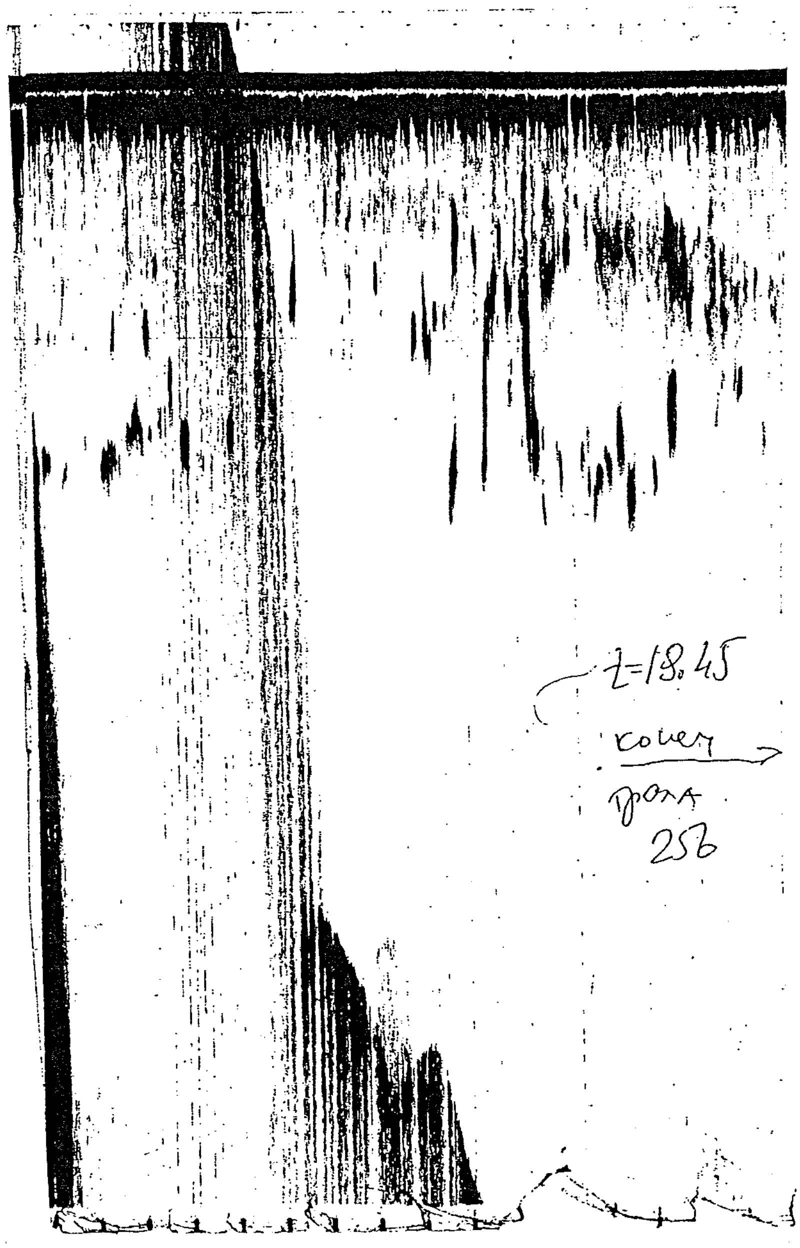

Figure 5: Echogram of krill swarms in the Coronation Island fishing ground, February 1990.

Figure 6: Echogram of krill swarms in the Coronation Island fishing ground, February 1990.

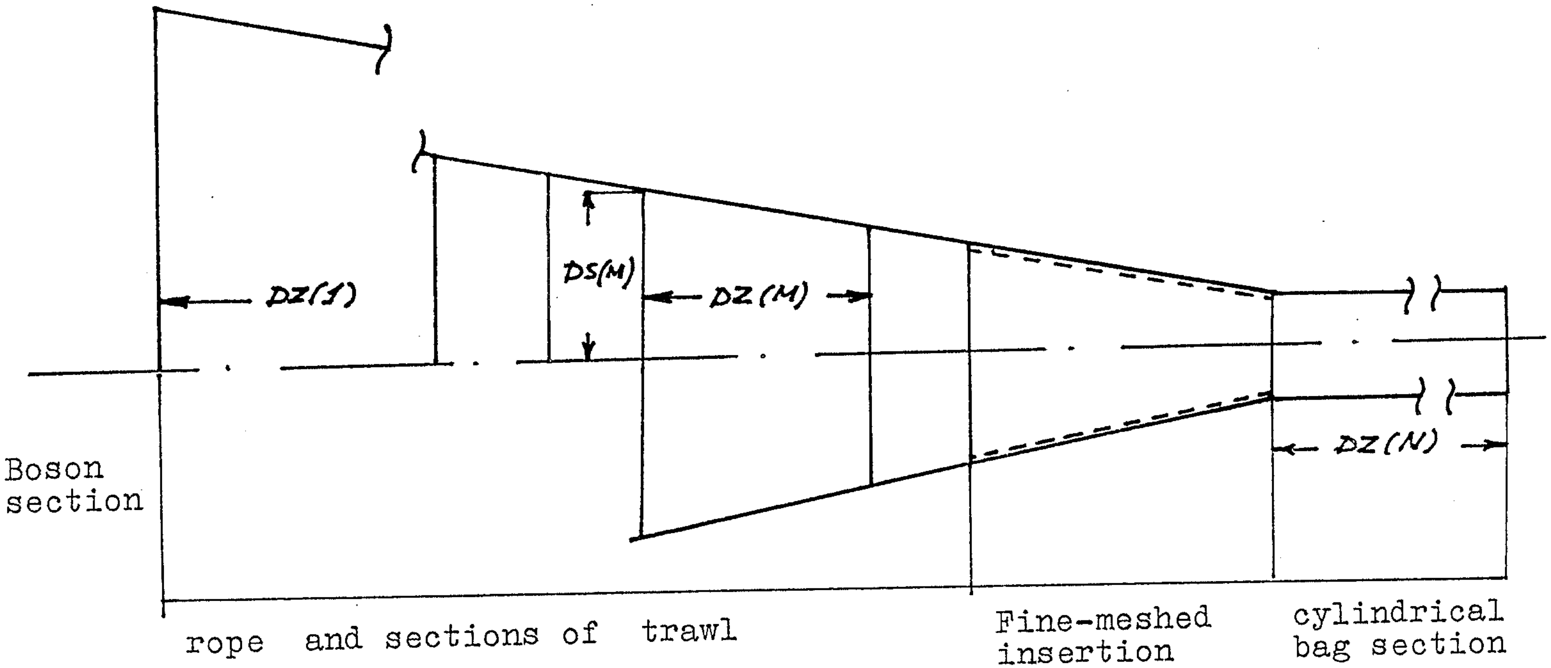

Figure 7: Design of trawl sections.

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