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The significance of fish behaviour in the evaluation of hydroacoustic survey data

by

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INTRODUCTION

Ever since echo sounding was introduced as a fish finding method it has been evident that certain limitations exist to the registering of fish in all conditions. Technical limitations related to the performance of the equipment as well as physical and acoustical conditions complicate detection when certain unfavorable fish behaviour occurs.

Hydroacoustic fish abundance estimation, as echo integration, involves several assumptions concerning the behaviour of fish. One assumption is that the average fish density beneath a surveying vessel is equivalent to the average fish density in the surveyed area. A second assumption is that differences in behaviour patterns in fish under varying surveying conditions will not be of significanse in the evaluation of hydroacoustic survey data, for instance when converting echo abundance into quantities fish.

The first assumption is usually looked upon and discussed as an exclusively statistical problem and the second assumption has long been simply overlooked because of lack of relevant data.

The significance of both these important presuppositions may be very closely connected to an eventual influence on behaviour of fish by the presence of the surveying vessel. In addition more general biological factors such as vertical migration and varying schooling densities in fish could be of considerable importance.

This report gives a summary of a number of experiments and in situ observations carried out in order to collect information on such phenomena.

Methods of observation.

Information regarding changes in fish behaviour caused by the approach of vessels cannot be obtained by use of convertional echo sounders located onboard the moving vessels themselves. Attempts have therefore been made to collect such data using a stationary, submerged echo sounder transducer positioned such that an approaching vessel passes directly over it (Olsen, 1979). Underwater photography and television observations have also been used in similar arrangements.

When running the onboard echo sounder (SIMRAD EK38 or EK120) with fast extend triggering (8 pr. sec.) and displaying the echo on a large graphic recorder (EPC 3200, 50 cm), greatly expanded displays of single fish echo traces have eben obtained. Such displays give improved precision in estimation of fish density through trace counting and are also used for studying whether significant movements of the fish take place during the recording.

As trace form analyses can only be done on resolved fish echo recordings, and most conditions are in practice unfavorable in this respect, other methods have to be used as well. One recent attempt has been to measure eventual doppler shifts in the received echo signals. The technique used has been to operate a modified "search light" sonar with the acoustic beam directed ahead/downwards at fixed tilt angles when passing concentrations of fish.

The investigations have been undertaken mainly in relation to herring concentrations found in Norwegian fjord areas during autumn/winter. Behaviour of fish in various size groups (10-35 cm) and positioned at different depths (10-100 m) have been lokked into. A few observations of reaction pattern in cod have also been made in the spawning area of Lofoten.

The vessels carrying out these investigations have been the research vessels R/V "JOHAN HJORT" (700 tonn/1500 hp) and R/V "JOHAN RUUD" (300 tonn/1000 hp).

Behaviour pattern in herring during passage of a vessel.

Fig. 1 shows an echo recording obtained by the submerged transducer directed towards surface at 48 m depth (Olsen, 1979). The recording illustrates the reaction pattern of a shoal of spawning herring at 10-20 m depth at night, during the approach and passage of R/V "JOHAN RUUD" at a speed of 9 knots. During the passage the herring is seen to undertake a fast downward migration (0.75 - 1 m/s). The descending reaction continues until a short while after the propeller of the vessel has passed.

Fig. 2 shows a similar echo recording obtained by the submerged transducer at 16 m depth directed downwards. The vessel is passing above scattered concentrations of medium sized herring ($\bar{l} \approx 25$ cm). During the passage the fish echo recording seems to partially disappear, but it is reestablished a few seconds later at increased depth.

Fig. 3 shows an example of an apparent complete disappearance of echo recording when the vessel is passing, followed by descent of the fish. The recording is obtained from dense concentrations of hibernating adult herring at night close to the surface.

An apparently less distinct, but still significant, descending reaction can be observed in Fig. 4 where R/V "JOHAN HJORT" is passing at 10 knots above a more scattered concentration of adult herring at 50-100 m depth.

When the pulse repetition speed and the recorder paper speed are increased, more detailed paper recordings are obtained. One example of such recording is shown in Fig. 5 where details of the vertical movement of single fish during passage of the vessel can be studied.

Underwater photographs taken within schools of herring at night give further information about the changes in behaviour which typically occur when a vessel is approaching. During one experiment 6 following runs crossed in different directions over the position of the underwater camera submerged at 35 m depth. In each run photographs were taken when the vessel approached, and all photographs taken at a surface distance of approxemately 40 m amd less ahead of the vessel, showed fish swimming in the same direction as the vessel. Photographs taken during passage of the vessel showed descending fish.

Underwater television observations made during day time with a camera lowered at various depths down to 40 m (facing upwards) have shown reaction patterns in herring during conditions where the fish also are affected by visual stimulation. A huge school of herring with a depth extension between 10-40 m, showed the first signs of changed behaviour when the approaching vessel was 75-100 m away. At a distance of 30-50 m the swimming typically became faster, "running away"-orientated and the first weak trend of descent appeared.

During the passage of the vessel the descent increased dramatically and may have reached downward swimming orientation of perhaps more than 60°. In some occasions the swimming behaviour seems to approach a stage of "panic" where the schooling formation is broken and the fish are "fleeing" downwards and out of the path of the vessel. During such situations the fish density was greatly reduced in this area. A few seconds after passage, the escaping behaviour rather suddenly dissappeared and the fish were soon swimming apparently totally related in their original manner.

Fig. 6 shows an expanded scale echo recording of a scattered concentration of herring ($\bar{l} \approx 25$ cm) obtained on the echo sounder onboard the research vessel (SIMRAD EK 120 + EPC rec.). Measurement of length and "inclination" of the recorded single fish traces are illustrated.

In Table 1 is presented estimates of maximum detection beam angle of the recorded fish, based on measurements of trace lengths (l)

$$l = \frac{v_p}{v_s} \cdot D \left(tg \left(\frac{\theta}{2} + \varphi\right) - tg \left(\frac{\theta}{2} - \varphi\right)\right)$$

v_p= recorder paper speed (mm/s), v_s= ship speed (m/s), D= fish recording depth (m), θ= detection beam angle, φ= transducer tilt (at measuring speed)

The recordings are obtained from experimental runs with R/V "JOHAN HJORT" above concentrations of small herring ($\bar{l} \approx 10$ cm). The estimated maximum detection beam angles appear in all runs to be greater close to the surface. In run II at 10 knots the angles are also significantly greater particularly at shallow depths than in run I at 4 knots.

Assuming that the difference in detection beam angles originates from movements of the fish during the recording, a difference in the order of 1°, as seen at the greatest depths, indicates a horizontal movement component in the ship direction of about 0.8 - 1 knots. At shallow depths, an estimated difference of $3\text{-}4^{\circ}$ indicates a movement of about 2-2.5 knots. An increasing downward tilt of the fish during the recording will, however, to some extent bias this result as this too will increase the detection beam angle (Olsen, 1979).

Trace inclination is a function not only of the movement of the fish, but also of the transducer tilt and directivity, the echo recorder scaling factors and the acoustic back scattering directivity pattern of the fish. A simple grafhic comparison has been used for estimating the expected trace form obtained from a 20 cm long herring swimming horizontally at a speed of 1 knot in the same direction as the ship (Fig. 7).

Table 2 compares the estimated mean inclinations obtained from measurements on the echo recording with the estimated theoretical inclination of a horizontally swimming fish. Apparently no significant downward migration of the recorded fish can be observed.

In Fig. 8a and b are shown two echo recordings of young herring concentrations made simultaneously by the onboard echo sounder and by the submerged echo sounder during the vessel passage.

By counting the number of echo traces and assuming an athwartship effective fish detection beam angle of the onboard echo sounder of 13° (- 6 dB), the average area fish density at 70-90 m depth in the vicinity of the submerged transducer has been estimated.

An attempt has been made to estimate the average area fish density recorded by the submerged transducer in the same depth interval by the degree of "echo recording saturation" in the paper recording. When assuming a minimum recording target strength of - 9 dB less than fish recorded on the acoustic axis, the corresponding effectiv detection beam angle approxemately is 16° and the mean sampling area at the depth interval between 70-90 m can then be calculated. Knowing the pulse length of an echo sounder the vertical target resolution can be calculated (sound speed · 1/2 pulse length) and when complete "echo recording saturation" is occuring at least 1 fish per minimum resolution depth interval is present.

Table 3 compares the estimated area fish densities at 70-90 m depth in 3 runs with R/V "Johan Hjort" at 10 knots above concentrations of young herring positioned at 50-100 m depth at night. The results seem to verify that the number of fish observed on the 120 KHz echo sounder onboard the vessel was considerably less than the fish stock present in the observed area. (≈ 20 %)

In Fig. 9 and 10 are shown diagrams of integrater output computed from magnetic tape recordings sequences of echo signals obtained on the submerged transducer. During the sequences of the passages presented in Fig. 9 (from the young herring runs) a reduction in the integrator outputs in the order of 85-95 % is observed compared to the mean output value before the vessel arrives. Fig. 10 shows passages through concentrations of adult prespawning herring positional closer to the surface (Fig. 3). The integrator outputs are in the instant of the ship transducer passage, reduced to a fraction (0.5-1 %) of the output when the fish were undisturbed.

In the area of Lofoten the spawning north - arctic cod are typically found in scattered concentrations at 100-150 m depth. In a few experiments with R/V "Johan Ruud" running at 8-10 knots above such fish concentrations, observing the behaviour of the submerged transducer, the cods showd a distinct descending tendency during passage. The reactions in the runs at 8 knots appeared to be significantly weaker than at 10 knots. A reason for this may be the dramatic increase in the noise generated from this vessel at the higher speed (Løvik & Pettersen 1981).

Other aspects of behaviour in fish which may influence the obtained echo abundance.

In Fig. 11 a and 11b are presented distributions of relative fish densities estimated by echo integration during two echo surveys undertaken in a restricted fjord area in northern Norway. Fig. 12a presents the results of a survey undertaken during day time and Fig. 11 b shows the results of an identical survey during the late evening. Previous knowledge of the general location area of the fish allowed the designing of a survey coarse grid, which to a great extent made both echo surveys effective in investigating the entire area where fish were distributed.

The estimates of total relative fish abundance obtained in the day survey compared to the abundance in the night survey gives a ratio of 1:2.4. The fish in the area were identifyed as medium-sized herring ($\bar{l} \approx 25$ cm) (about 90% of the numbers), some small herring and capelin ($\bar{l} \approx 10$ cm) and a few (<1%) bigger cod family fish.

In Fig. 12a and 12b are shown typical echo recordings of the fish concentrations seen during the surveys. It is evident that a definite change in behaviour of the fish takes place. The bottom schools seen during daytime disappeared at night and later became distributed in an intermediate pelagic scattering layer.

The result of this investigation seems to support what possibly is a common experience in survey work, that a considerable underestimation may take place when fish concentrations are mainly located close to the bottom.

Several explanations are possible for such a discrepancy. For instance a faulty TVG function in the echo sounder may easily produce such results. A more obvious explanation would be an effect of the general technical short-coming in integration of fish echos too close to the bottom. In the common echo integrater system used, The technical solution for avoiding echos from the bottom itself is, for example, to stop integration ½ ms before the bottom echo appears. This technique may frequently under the above conditions also reduce the amount of fish echos for integration.
A third explanation, but perhaps still to be trated as speculative, is the effect of vertical migration of fish on target strength. If, for instance, a downward migration takes place without a corresponding pressure equalization in the swimbladder, the excess pressure may change both the form and the volume of the bladder and quite possibly alter the target strength of the fish. Such a deformation has been shown by taking X-ray photos of a herring which, inside a pressure chamber, was artificially "descended" (Olsen, 1980).

When dense schools of fish are registered on conventional echo sounding equipment the signal strength frequently rises to a level which, unless special precautions are taken, produces what is known as artificial "bottom-blocking" (white line). Besides this technical difficulty there is an acoustical problem. This is the effect of signal strength reduction when sound passes through heavy concentrations of sound scatters ("shaddowing").

Investigations made by RØttigen (1975), estimating the fish density necessary to cause such an effect to become significant, indicated that with a schooling density of 200 fish pr. m^3 or 2,5 kg fish pr. m^3 ($\bar{l} \approx 12$ cm), the acceptable depth extension limit of the school was in the order of 25-30 m. If the schooling fish are bigger, an increased depth extension of the school may still be save.

The critical factor, besides the fish size, is then the schooling density. Estimates of fish density within schools of adult herring have been attempted both by purse seine catches (Aasen, 1955) and by underwater photography (Truskanov and Scherebino, 1966). Aasen estimates fish density of schools in the spawning period to be 2-5 fish pr. m^3 and Scherebino et al. give a figure of ≤ 5 fish pr. m^3 in schools in the early prespawning stage.

Some new photography of hibernating adult herring schools have been obtained by lowering a remote controlled camera into fish schools located by echo sounder. In order to avoid noise disturbance from the research vessel the camera equipment was usually operated from a small boat. On the camera housing was also mounted an echo sounder transducer which "observed" approximately the same angle of view as the camera. Whenever fish were recorded on the camera echo sounder at acceptable photographic ranges, pictures could be taken using electronic flash.

Density estimates obtained from day pictures (schools at 20-40 m depth) are typically in the order of about 10-20 fish p. m^3. Density estimates obtained from night pictures (schools at 10-30 m depth) also give average figures in the order of 10-20 fish pr. m^3. The highest fish densities seen both on day and on night pictures have been estimated to about 50 fish pr. m^3 (Fig. 13).

These estimated schooling densities are 2-10 times higher than earlier findings. The aggregations of herring from which the pictures were taken are from fjord areas where herring in historical times have been known to occur. It is not known, however, if these areas for some reasons are especially suited for maintaining such high concentrations of fish.

An approximate calculation of the depth extension in such schools before acoustic "shaddowing" occurs, shows that roughly only the upper 5-10 m of a school, which often has a depth extension of 50 m or more, will give a "correct" back scattering.

Discussion.

The subject delt with in this report concerns aspects of acoustic fish abundance estimation which are believed to be of vital importance for accuracy.

An assumtion that fish density observed by the echo sounder onboard the surveying vessel always is to be relied on as representative for the true fish density in an area, may have been demonstrated as beeing rather hazardous.

This problem is not only related to a real density reduction caused by escaping behaviour of the fish. Apparent density reductions due to shortcommings in the necessary dynamic sensitivity range of the equipment, when detecting fish targets in "unfavourable" acoustic back scattering positions (downward tilt) are probably more common.

The behaviour of the main species investigated, herring, is probably camparable to a great number of related species. The observed "nervous" behaviour may be looked upon as a part of the natural defence mechanism, and even if varying biological conditions may modify the degree of "nervousness", the main characteristics in the behaviour pattern will probably always be present.

Perhaps more surprising is the observation of an apparently significant avoidance behaviour cod in Lofoten. This species is known to show behaviour patterns very far from "nervous" under most conditions. These results may, however, need some further vertification.

To which extent differences in avoidance behaviour will exist between fish in scattered aggregations compared to schools is not sufficiently investigated. There is clearly a greater posibility of "neighbour-interaction" when fish are schooling.

Another aspect, still not fully understood, is the way the depth distribution of the fish may affect the reaction pattern. In relation to acoustic fish abundance estimation this aspect, seems to focus attention both on the echo registration process and on the applied methods of converting echo abundance into fish abundance.

One fundamental short-comming in the today common methods of echo abundance converting is the indapability of handling any dynamic process in the behaviour of fish. Establishment of "converting-constants" ("C-values") an hardly achivable as recording conditions/ biological factors an continously changing. More meaningful would probably be to formulate functional relationship where for instance variables describing fish behaviour also are incorporated.

The results of the reported experiments may give some of the informations needed to allow the formation of a sufficiently precise model for a mathematical description of the behaviour. It is believed that such model will be necessary in the future for improving the converting of echo abundance (Foote, 1979, Soumala & Yudanov, 1979).

Another approach towards the improving of the solution to these problems would be the development of good enough observation methods for describing the instantaneous behaviour of fish during recording; not only resolved single fish, but also dense concentrations.

Promising results in the development of such a method has been obtained in the earlier mentioned experiments which measured doppler-effects of the fish beneath the vessel. Both in experiments on herring at 25-75 m depth and on cod at 80-120 m depth, the obtained doppler-shift measurements could be shown to be in fair agreement with the behaviour observation made by the echo sounder.

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Table 1. Estimated maximum detection beam angle of herring ($\bar{l} \approx 10$ cm) recorded in different depth by echo sounder (SIMRAD EK120). (Based on measurements of maximum echo trace lengths, (means of 10 longest traces)). Runs at 4 and 10 knots.

Depth	Maximum detection beam angle	
	4 knots run	10 knots run
25	13.9°	16.0°
35	12.8°	15.4°
45	12.7°	13.8°
55	12.8°	13.4°
65	12.0°	13.5°
75	11.6°	13.2°
85	12.0°	13.2°
95	12.0°	12.6°

Table 2. Estimated mean "inclination" of 100 fish in each depth interval (longest traces), compared with the estimated "inclination" of a horizontally swimming fish ($10^{\circ} + 3^{\circ} = 13^{\circ}$ detection beam angle)

Depth	Observed mean "inclination"	Estimated "inclination" hor. sw. fish
25	1.6	1.8
35	2.3	2.5
45	2.5	3.2
55	3.3	3.9
65	4.3	4.6
75	4.7	5.3
85	4.8	6.0
95	5.1	6.8

Table 3. Estimated fish density registered by the submerges stationary echo sounder (SIMRAD EY-M) and by the ship mounted echo sounder (SIMRAD EK-120), when passing concentrations of herring ($\bar{l} \approx 10$ cm) at 50-100 m depth at night (R/V "Johan Hjort", at 10 knots).

	Submerged echo sounder (EY-M)			Ship mounted echo sounder (EK-120			
	Mean sampl. area (m^2) at 70-90 d. (16°/-9dB)	Registration "saturation"	Sampling area x) fish dens. (fish/m^2)	Mean sampl. area (m^2) at 70-90 d. (13°/-6dB)	Fish count. pr. 1/10 mile	Sampling area x) fish dens. (fish/m^2)	Rel. fish dens. EY-M/ EK-120
Run 1	76	0.5	$6.6\cdot10^{-3}$	$3.4\cdot10^{-3}$	87	$1.3\cdot10^{-3}$	5.1
Run 2	"	0.6	$7.9\cdot10^{-3}$	"	99	$1.5\cdot10^{-3}$	5.3
Run 3	"	0.9	$1.18\cdot10^{-2}$	"	174	$2.6\cdot10^{-3}$	4.5

x) Within the minimum vertical distance of target resolution of the EY-M sounder: $(\frac{1}{2}\cdot C\cdot\tau) \approx 0.5$ m.

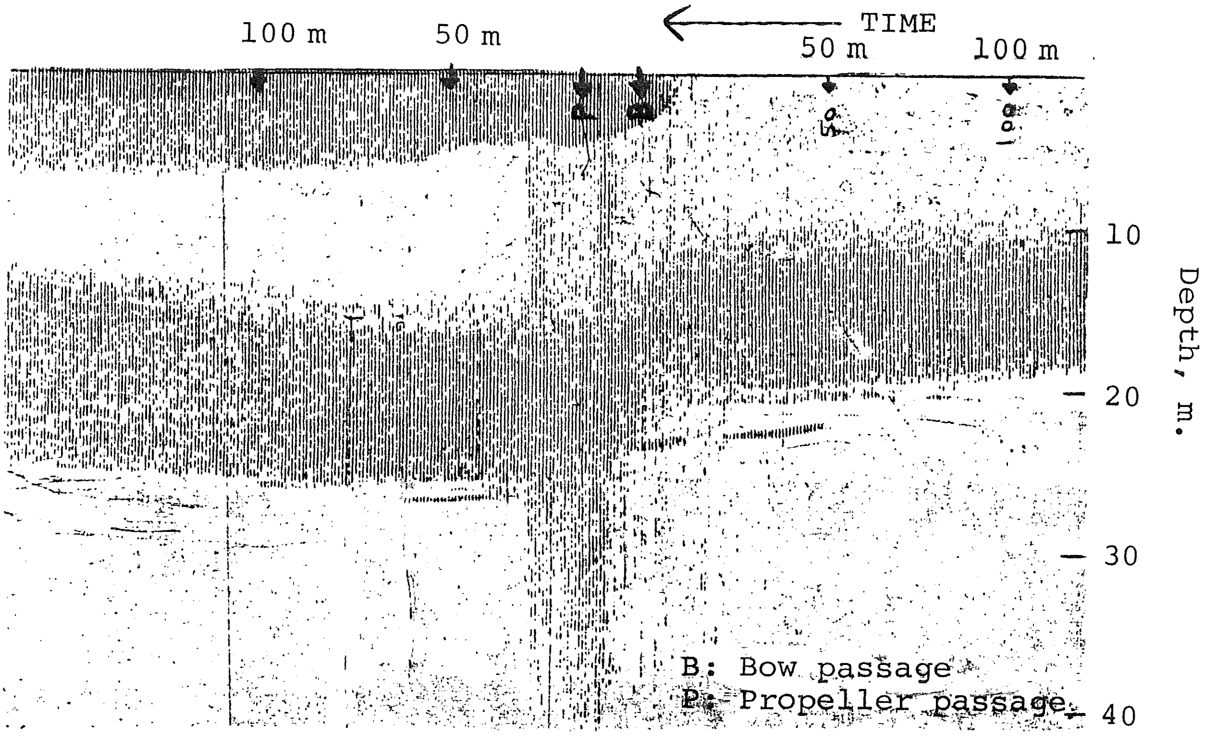


Fig. 1. Echo recording of prespawning herring at night obtained during passage of a submerged echo sounder transducer (SIMRAD EY) at 48 m depth facing towards surface (R/V "JOHAN RUUD", run at 8 knots) (expanded time-scale).

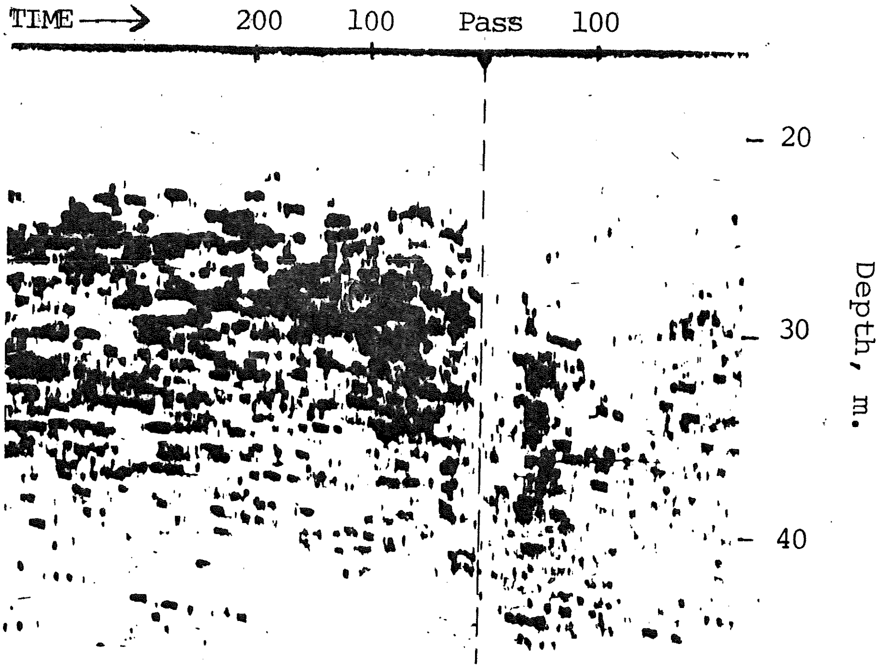


Fig. 2. Echo recording of herring (l ≈ 25 cm) at night obtained during passage of the submerged echo sounder transducer at 16 m depth facing downwards (R/V "JOHAN RUUD", run at 8 knots).

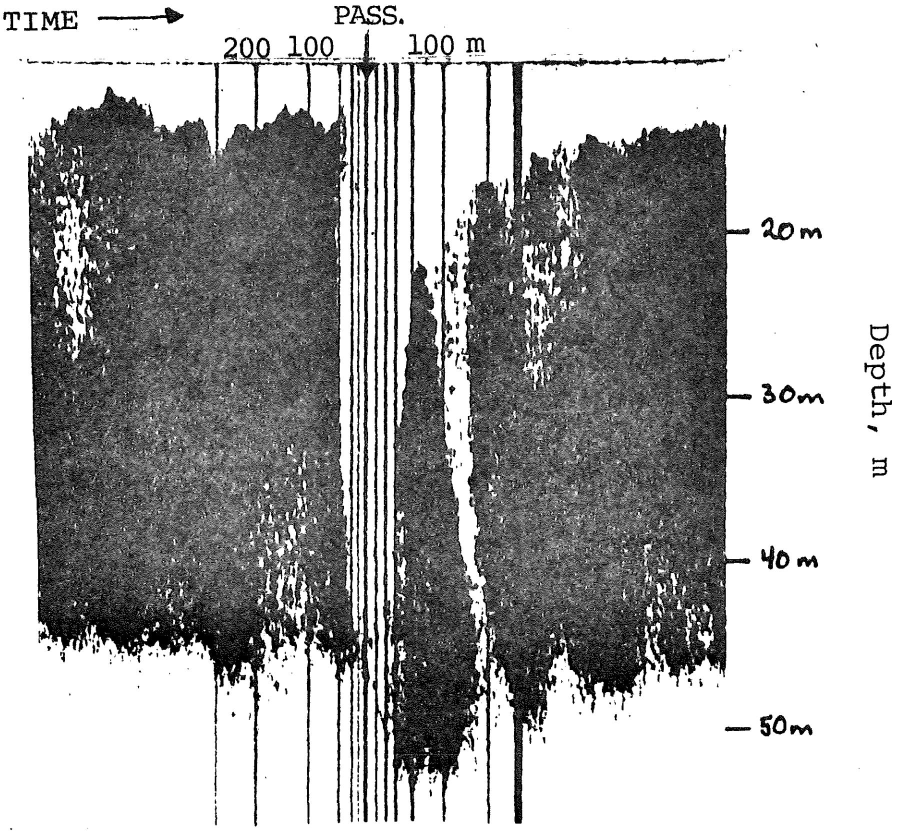


Fig. 3. Echo recording of prespawning herring at night obtained during passage of the submerged echo sounder transducer at 10 m depth (R/V "JOHAN RUUD", run at 9 knots).

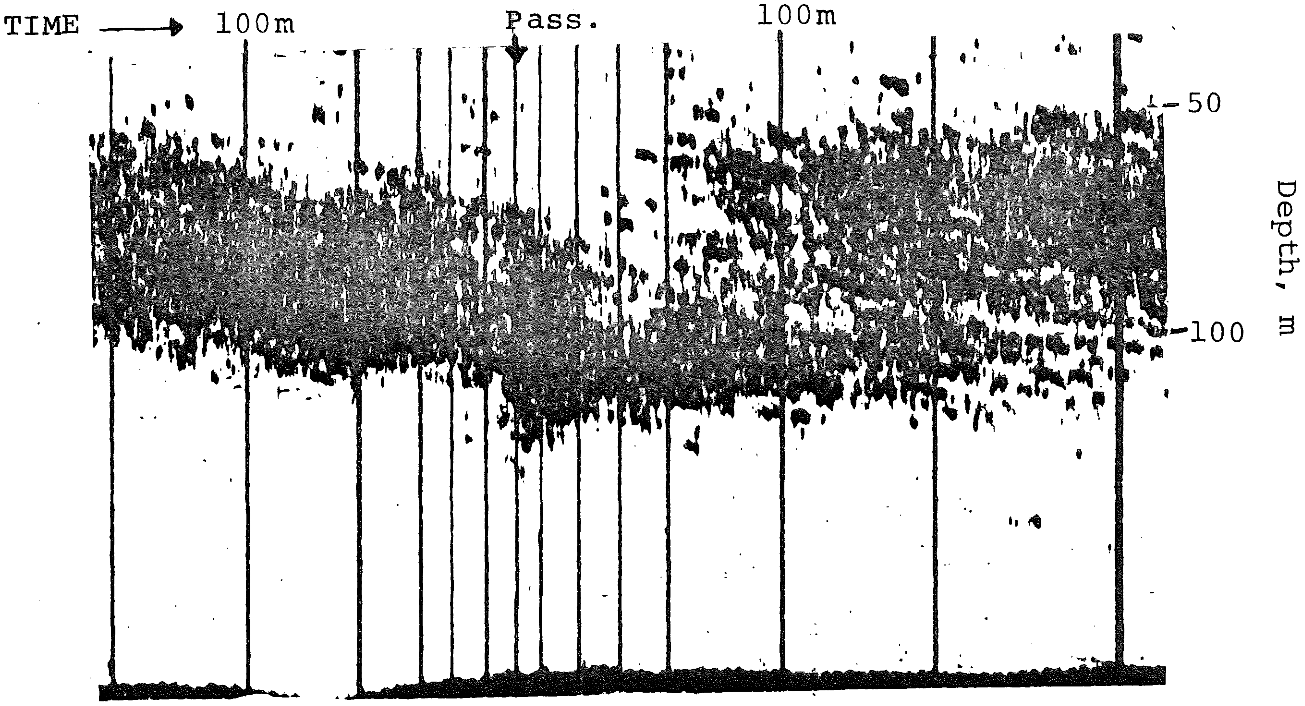


Fig. 4. Echo recording of herring ($\bar{l} \approx 28$ cm) at night obtained during passage of the submerged echo sounder transducer at 40 m depth (R/V "JOHAN HJORT", run at 10 knots) (expanded time-scale).

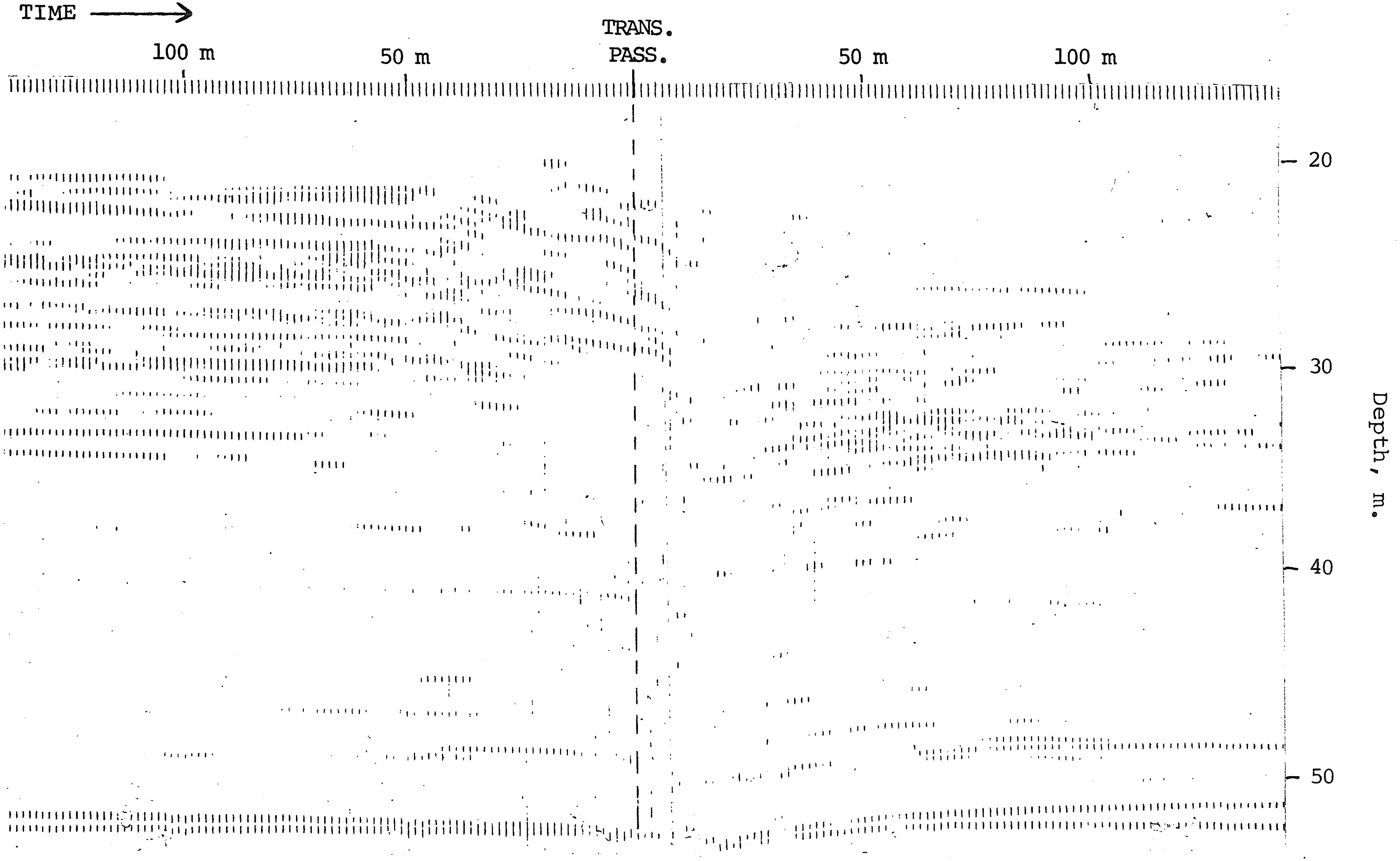


Fig. 5. Expanded time-scale echo recording (recorder paper speed 5 mm/s) of herring ($\bar{l} \approx 25$ cm) at night obtained by the submerged echo sounder transducer (R/V "JOHAN RUUD", run at 8 knots).

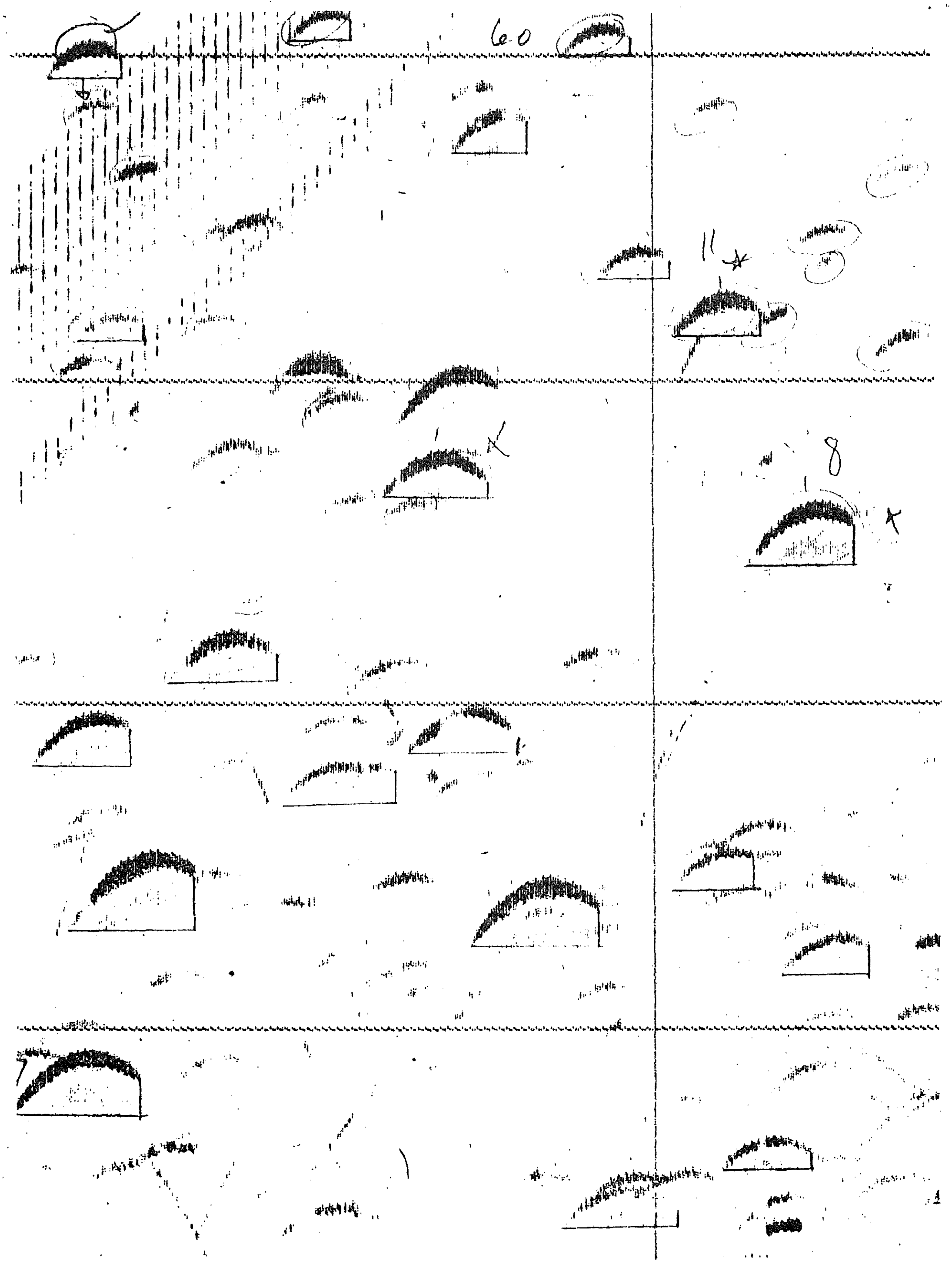
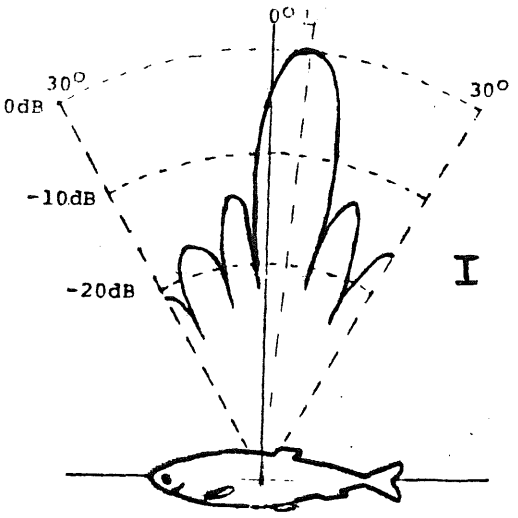
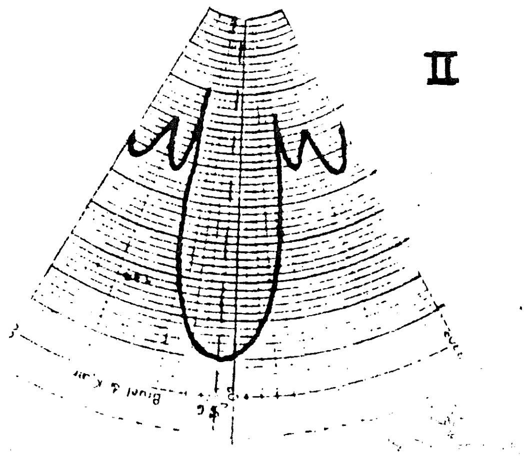


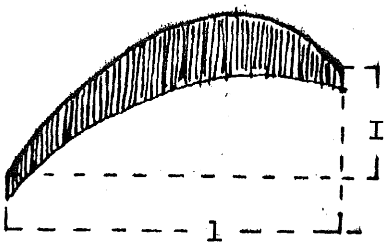
Fig. 6. Expanded scale echo recording of herring ($\bar{l} \approx 25$ cm) obtained on the ship mounted echo sounder (SIMRAD EK-120) in combination with a 50 cm graphic recorder (EPC 3200) (R/V "JOHAN RUUD", run at 8 knots).



1. step: Estimation of the resulting back scattering directivity pattern of a fish by "multiplying" the directivity diagrams I and II.



2. step: Definition of minimum recordable fish target strength less than fish recorded on the acoustic axis, and estimation of the true maximum detection beam angle from the above directivity pattern.



3. step: Estimation of the "inclination" (I) of a horizontally swimming fish:

$$I = k \cdot D\left(\frac{1}{\cos \theta_1} - \frac{1}{\cos \theta_2}\right)$$

where D = measuring depth
k = recorder scaling factor
$\theta_1 + \theta_2$ = true maximum detection beam angle
θ_1, θ_2 = beam angles "ahead" and "behind" the perpendicular.

Fig. 7. Diagrams illustrating a method of graphic comparison for estimating the expected trace form recorded from a 20 cm long herring swimming horizontally at a speed of 1 knot in the ship sailing direction "trace inclination": I .

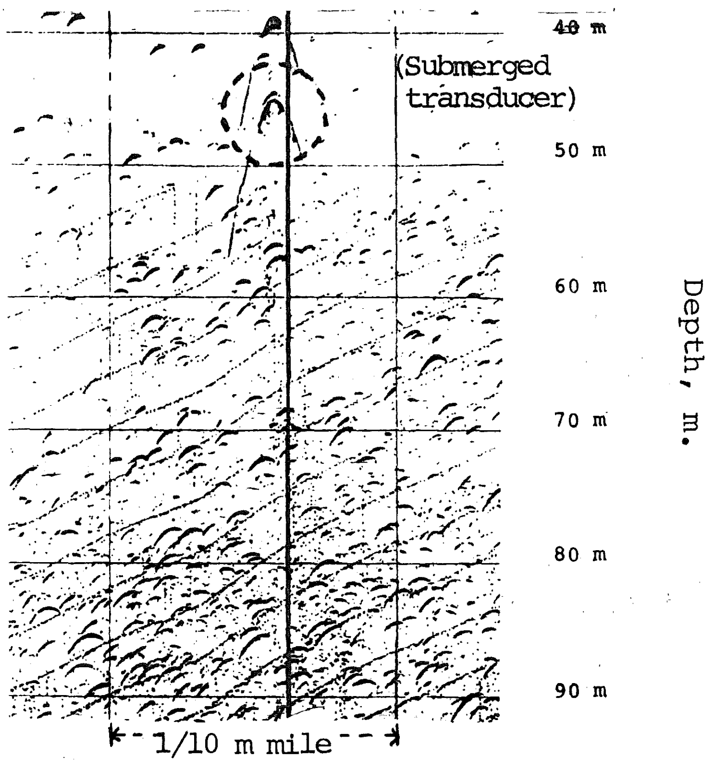


Fig. 8a. Echo recording obtained by the echo sounder (SIMRAD EK-120 KHz) onboard the R/V "JOHAN HJORT" during a run at 10 knots above concentrations of small herring ($\bar{l} \approx$ 10 cm) at night (from Olsen,1980) (reduced scale).

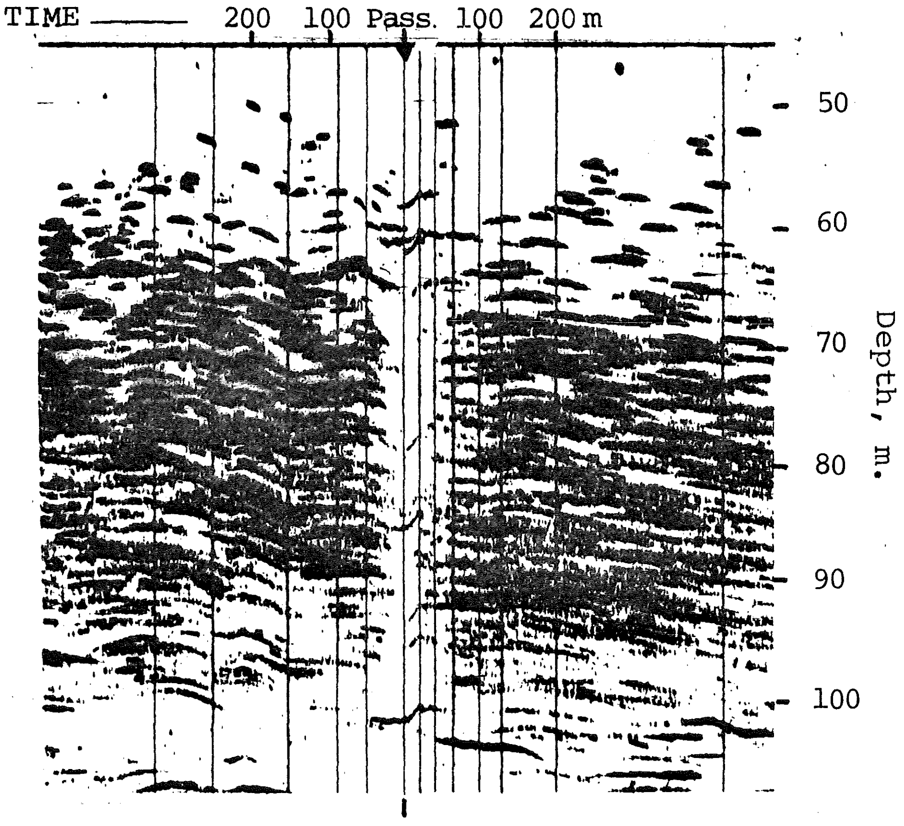


Fig. 8b. Echo recording obtained by the submerged transducer (SIMRAD EY-M, 70 KHz) at 45 m depth during the same experiment as above (Fig. 8a) (reduced scale).

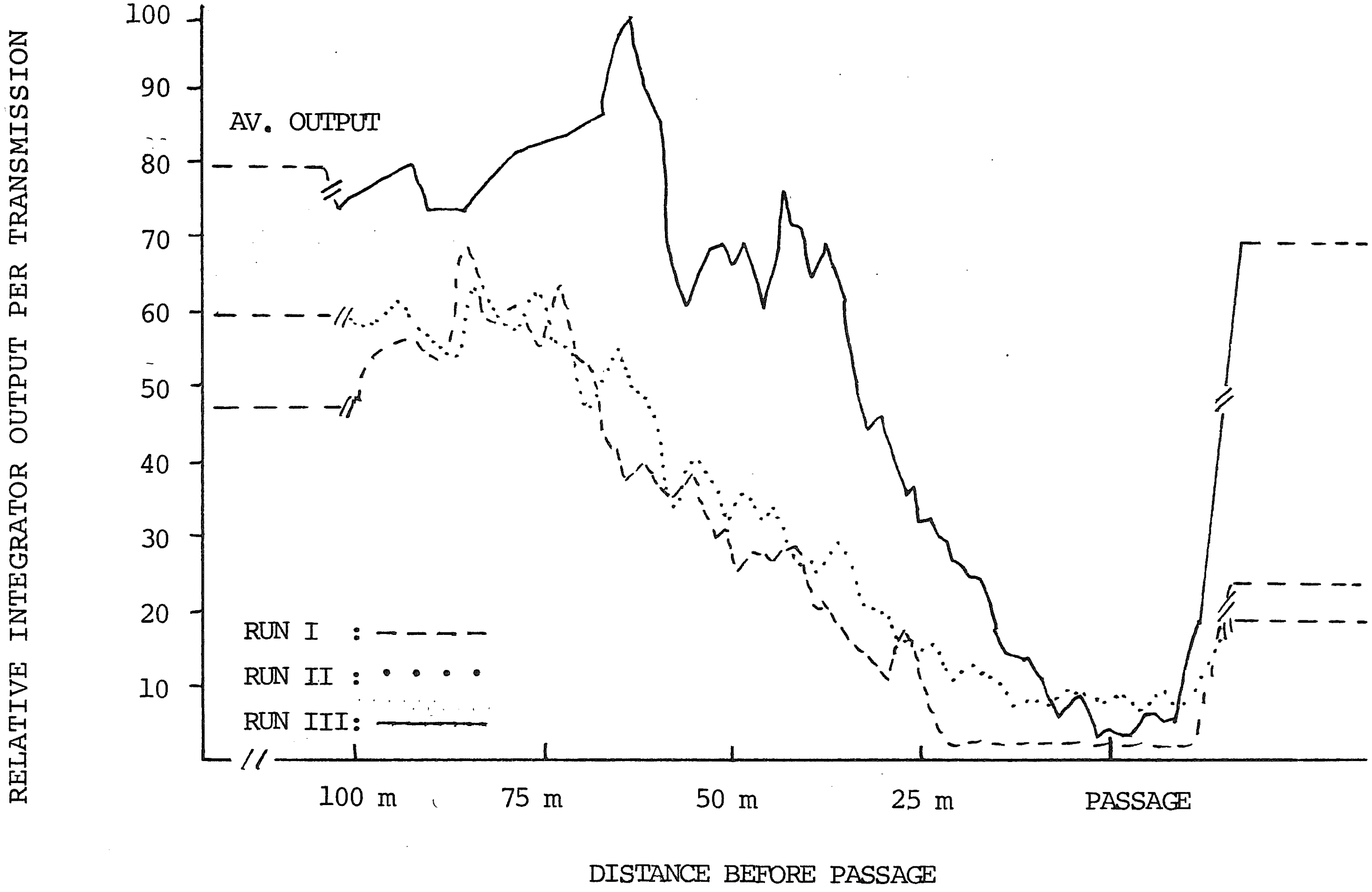


Fig. 9. Relative integrator output per transmission computed from echo recordings of young herring ($\overline{l} \approx 10$ cm) obtained by the submerged transducer (R/V "JOHAN HJORT", run at 10 knots) (Fig. 8b).

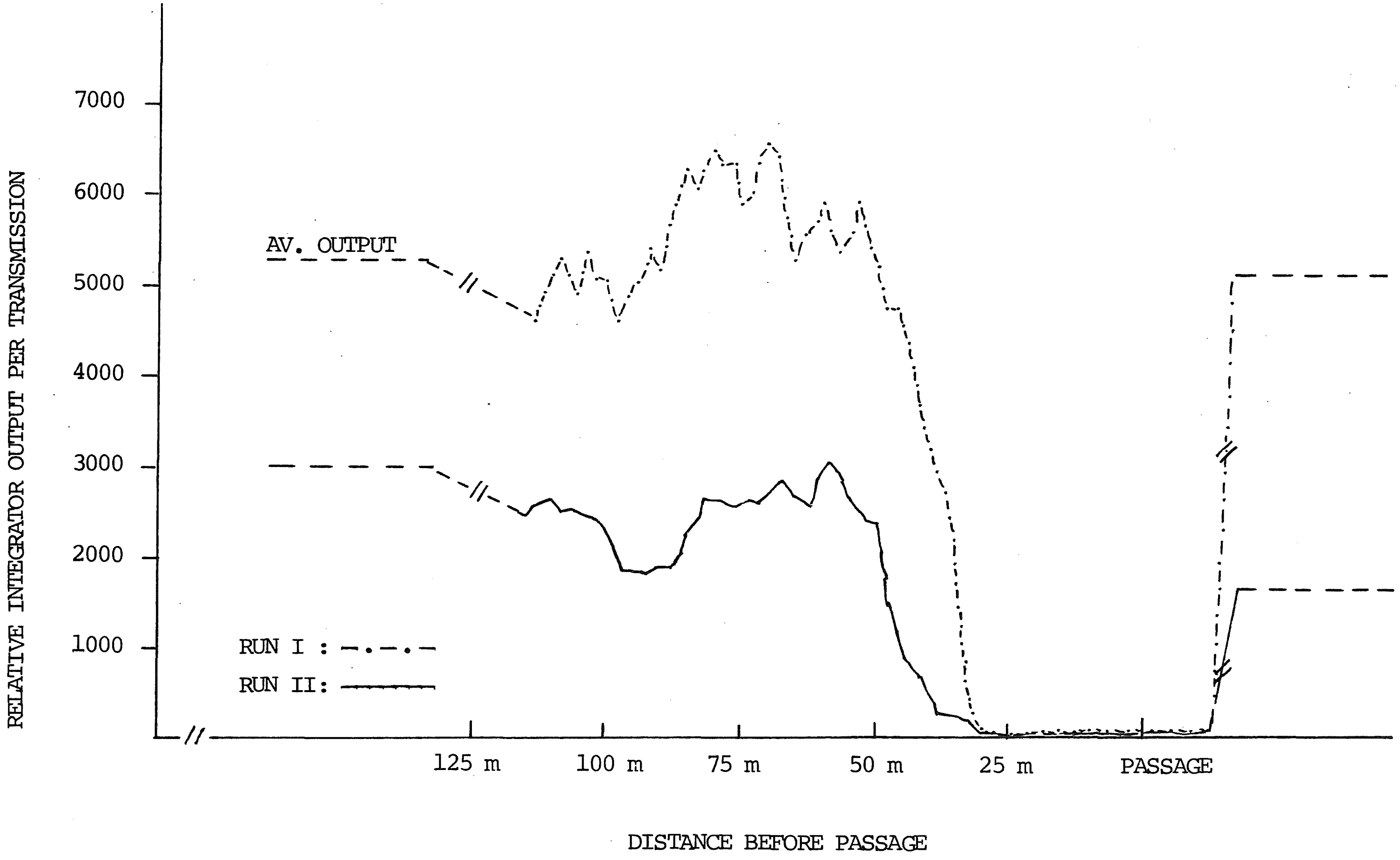


Fig. 10. Relative integrator output per transmission computed from echo recordings of prespawning herring obtained by the submerged transducer (R/V "JOHAN RUUD", run at 10 knots) (Fig. 3).

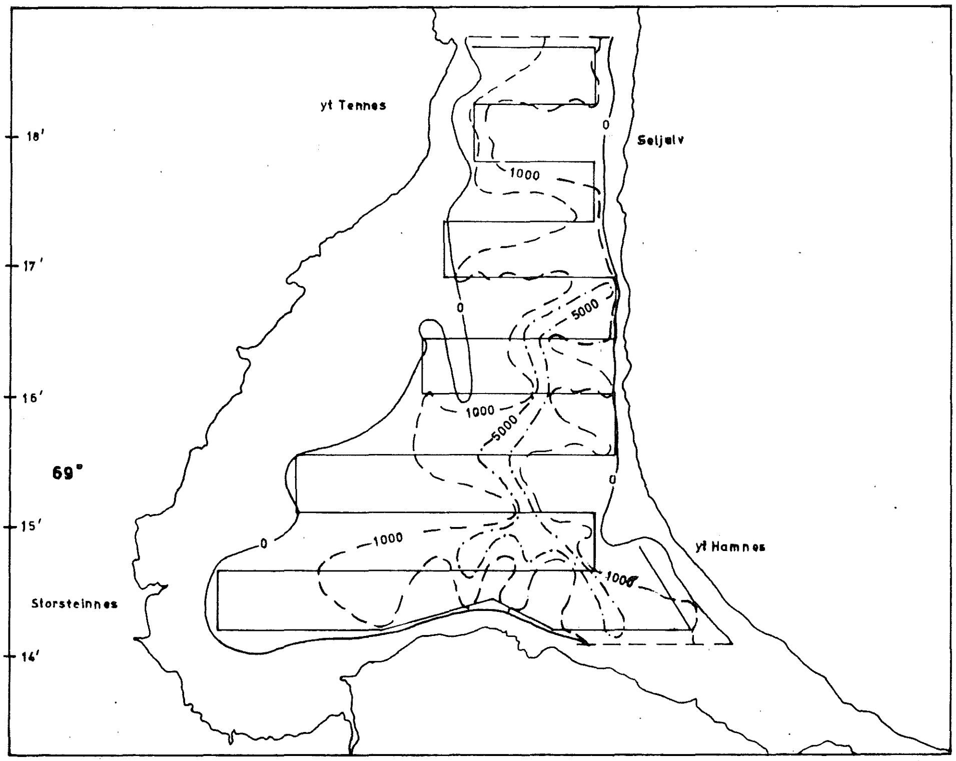


Fig. 11a. Distribution of relative fish abundance obtained by echo integration (SIMRAD EK 38 kHz + digital echo integrator) in Balsfjorden, March 1980. Day survey. Average echo abundance pr. n. mile sailed: 16100 integr. units.

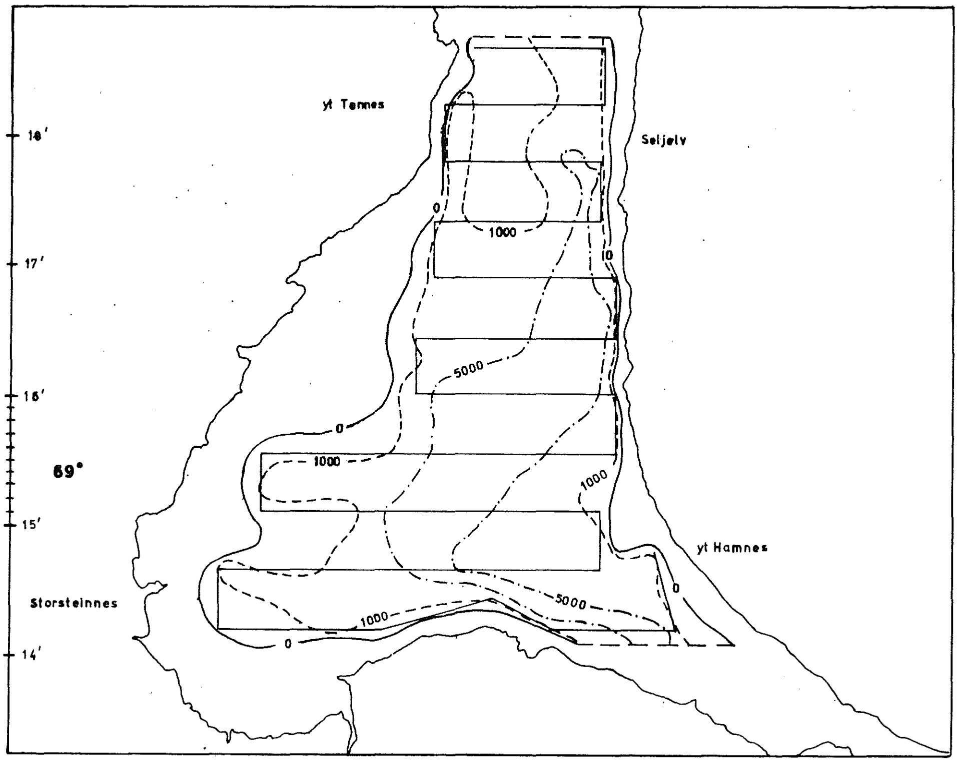


Fig. 11b. Distribution of relative fish abundance obtained by echo integration (SIMRAD EK 38 kHz + digital echo integrator) in Balsfjorden, March 1980. Night survey. Average echo abundance pr. n. mile sailed: 37600 integr. units.

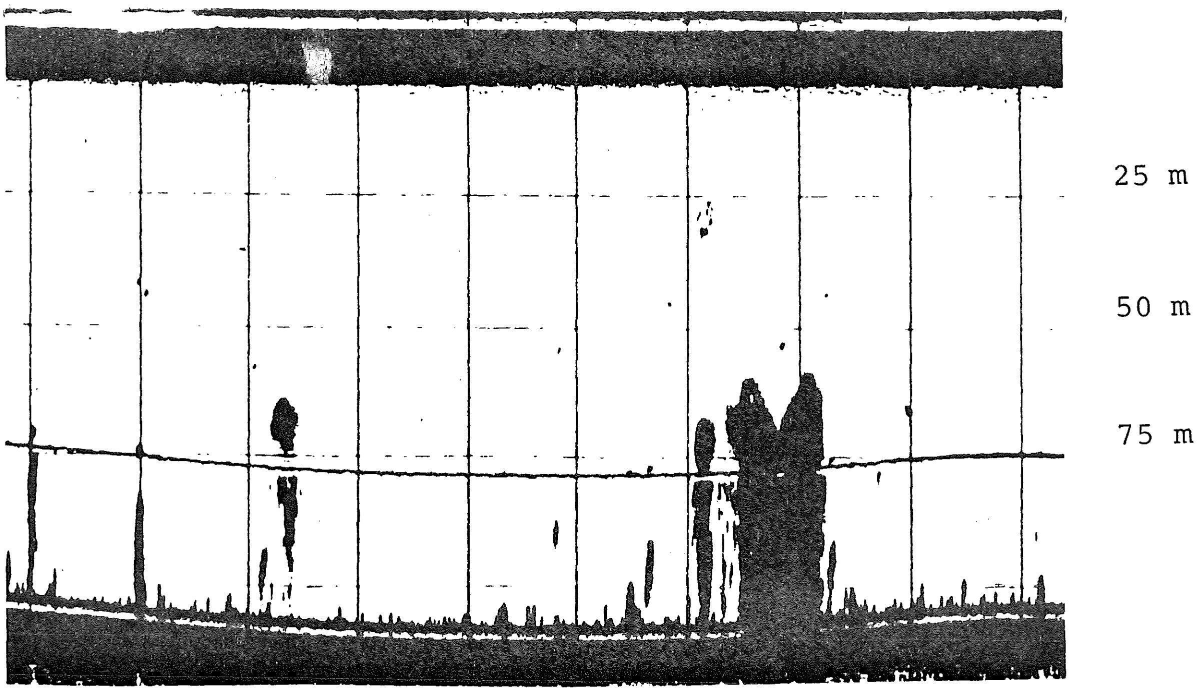


Fig. 12a. Echo recording showing typical vertical distribution of fish in Balsfjorden in March 1980 during a day echo survey.

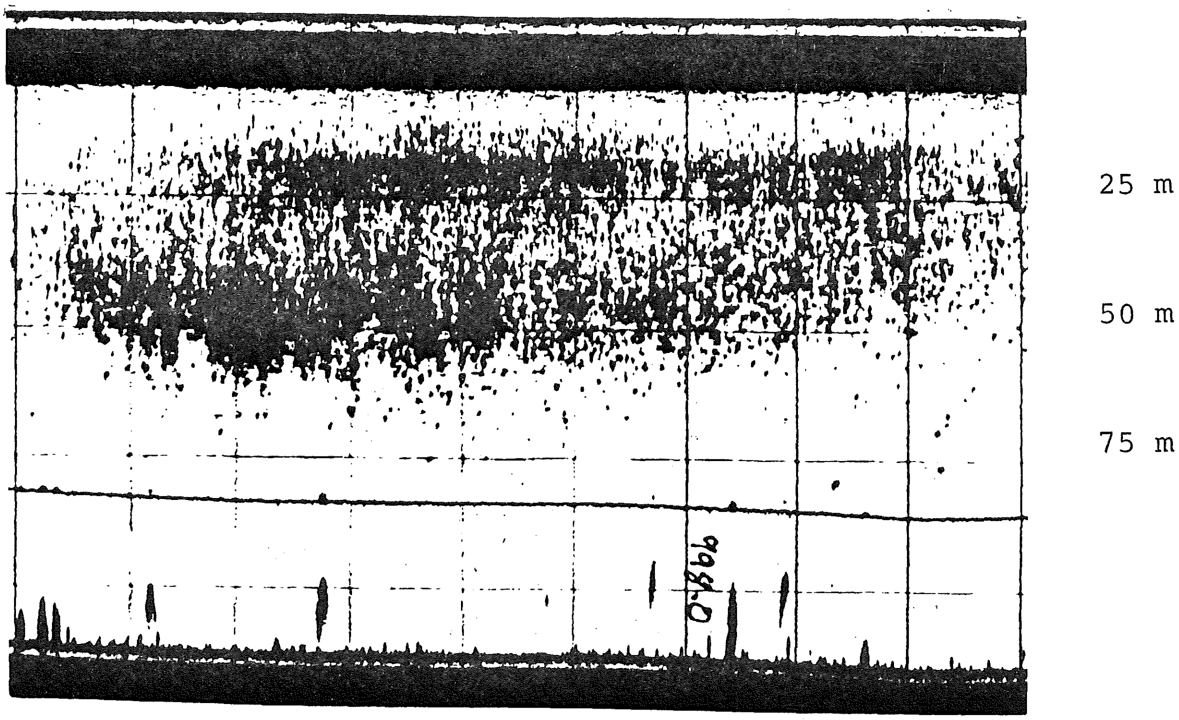


Fig. 12b. Echo recording showing typical vertical distribution of fish in Balsfjorden in March 1980 during a night echo survey.

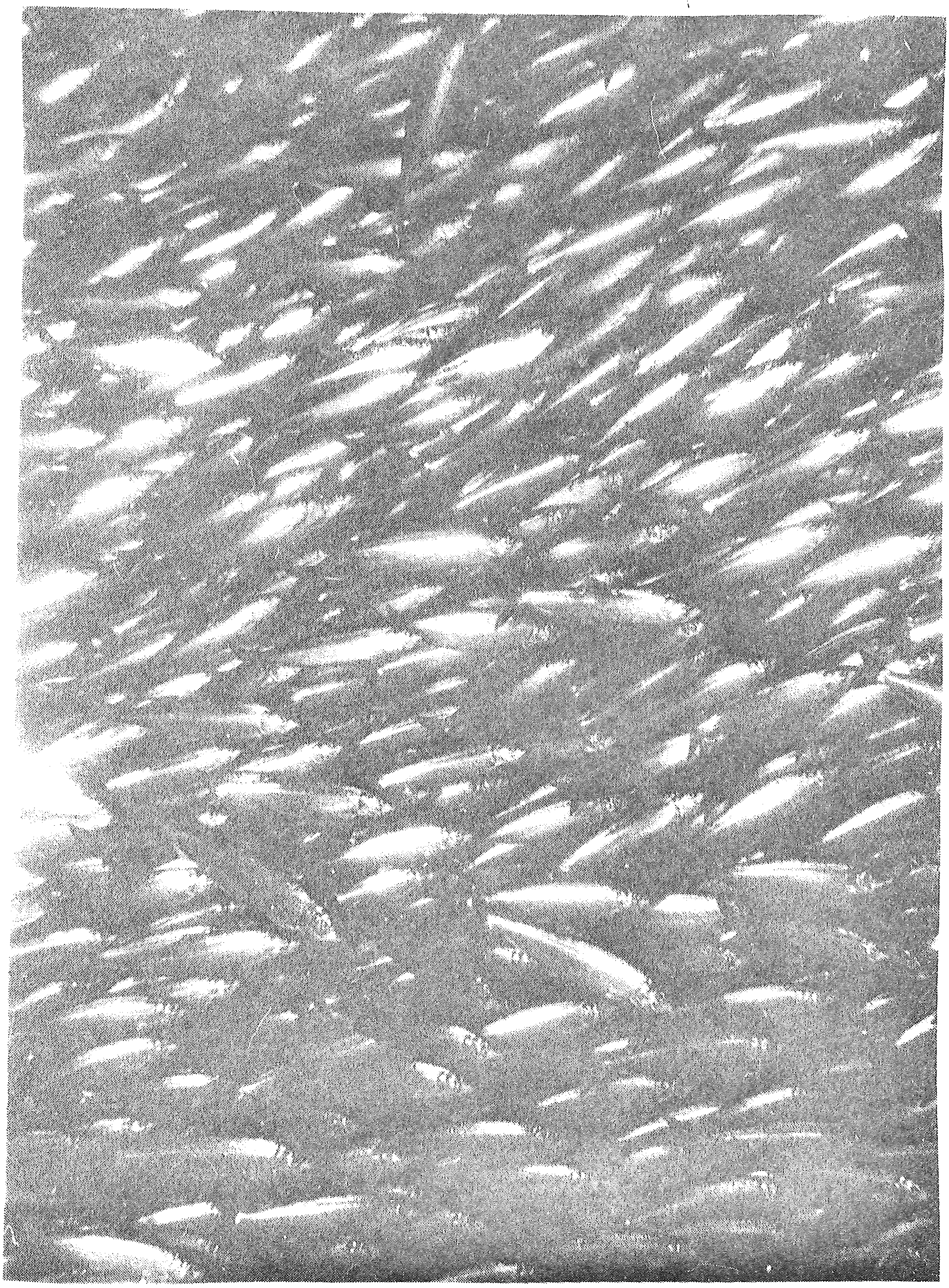


Fig. 13. School of hibernating adult herring ($\bar{l} \approx 32$ cm) photographed at night at 25 m depth. Estimated schooling density: 45-50 fish per m^3.