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SWIMMING BEHAVIOUR OF FISH SCHOOLS IN THE NORTH SEA DURING ACOUSTIC SURVEYING AND PELAGIC SAMPLING TRAWLING

by

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ABSTRACT

Swimming behaviour of schooling herring, mackerel and sprat, when approached by a survey vessel, was observed by aid of a true motion sonar. Observations were made both during surveying and during pelagic trawling. Horizontal swimming speed was clearly length dependent, but there were great variations from one school to another, even if the school members were of similar size. Generally the schools seemed to be guided by the approaching vessel, but often the schools avoided the path of the vessel. An attempt is made to quantify the influence of vessel-avoidance and upper blind zone distribution on the total abundance estimate. By taking advantage of the guiding effect, and modifying the gear rigging, the capture success of the pelagic sampling trawl was clearly increased.

INTRODUCTION

A basic assumption of the conventional echo integration method for fish abundance estimation (Dalen and Nakken 1983, Johannesson and Mitson 1983) is that the presence of a research vessel has insignificant influence on the fish behaviour. If fish tends to escape out of the path of an approaching vessel or flee downwards with a negative tilt angle, significant underestimation of fish densities may occur (Aglen 1989, Olsen 1987, Olsen et al. 1983 a). Due to the beam geometry, horizontal avoidance becomes increasingly critical the nearer the transducer the fish occure. Fish above the transducer depth is not detected at all.

Modern steel-hulled, diesel-engined research vessels generate low-frequency sound (Mitson 1989) which is within the hearing range of teleosts (Hawkins 1986). Olsen et al. (1983 b) put forward an avoidance model assuming that a sudden increase in the vessel generated sound preassure gradient is the releasing stimulus for avoidance reaction. Misund (1990) shows that the swimming behaviour at some distance may be influenced by a presumed directivity of the vessel generated sound (Urick 1967). That vessel avoidance is a common reaction among different species is shown by several descriptive studies (Boklach 1989, Diner and Masse 1987, Freon and Gerlotto 1988, Olsen 1971, 1976, 1979, Ona and Toresen

1988 and Neproshin 1979) and also by investigations where the avoidance has been quantified (Aglen 1985, Goncharov et al. 1989, Misund 1990 and Olsen et al. 1983 a).

This paper presents studies on the swimming behaviour of herring and sprat when approached by a research vessel. The observations are compared to the mentioned avoidance model (Olsen et al. 1983 b). The observations were made during an echo integrator survey in the North Sea, and we have tried to quantify the effect of vessel avoidance and upper dead zone distribution on the survey results.

During acoustic surveys midwater trawling is required to identify and sample pelagic recordings. When trawling the vessel noise increases (Chapman and Hawkins 1969). This may elict strong avoidance reactions leading to poor catching success (Godø and Ona 1987, Ona and Chruichshank 1986, Ona and Toresen 1988 b). If schooling, the fish may be particulary difficult to catch with a trawl (Pitcher and Wyche 1983, Taylor 1968), but there may be large regional and seasonal differences in the fish-to-gear reactions. Mohr (1969, 1971) found that migrating herring schools were very difficult to catch by midwater trawls, but schools on the spawning grounds were effectively fished by the same gear.

With the aim of increasing the catch efficiency on schools, we have quantified the swimming pattern of herring and sprat during trawl trials. We have also studied the effect of slight modifications in the gear rigging and vessel operation during trawling near the surface.

MATERIAL AND METHODS

The observations were made onboard R/V "Eldjarn" (1043 GRT, 3400 Hp) during echo integrator surveys on North Sea herring during July 1988 and 1989 (Figure 1). Some sonar measurements were made while the vessel were heading along predetermined transects. In most cases the regular echo integration was interrupted and the heading of the vessel was adjusted to point directly at the school singled out on the sonar. Often this required a reduction of the vessel speed.

The vessel was equipped with a multibeam sonar, Simrad SM 600 (Bodholt 1982). The operation mode chosen was a 85^0 horizontal beam fan resolved in 17 beams (5^0) on the sonar display. The vertical beam width was 7^0 (between 3 dB points). For behaviour observations and during trawling a true motion presentation was chosen and the display were recorded on video tape by aid of a palcoder. A target tracking mode was usually applied to support a presice navigation. An overwiev of the number of schools recorded when the vessel was cruising or trawling is given in Table 1.

For pelagic trawling a Fotø herring trawl was applied. The vertical opening varied between 12 and 20 m depending on towing speed and warp length. The distance between wings should be in the order of 30-35 m according to model tests. When conducting pelagic trawl trials, selected midwater or bottom schools were approached from a distance of more than 1000 m at a speed of about 4 knots. A trawl symbol was set at an approximate correct position on the display by taking account of the warp and bridle lengths. This symbol follows behind the vessel symbol along an ideal path. It was helpful when manouvering the trawl towards a recorded school.

The vertical position and opening of the trawl was monitored by a Simrad 50 kHz net sonde mounted on the headline. The vessel was usually navigated directly over the schools to measure their depth on the echo sounder. After passage the school could usually be recorded on the sonar as the trawl approached.

In 1989 a modified tecnique was tried for near surface schools. A large buoy (400 litres) was attached to each upper wing. Then the trawl could be kept close to surface at longer warp lengths (140 m) and by moderate turns with the vessel the trawl could be kept outside the propeller wake. The vessel was navigated to the side of and partly around the school (Fig. 3b). The trawl doors could usually be recorded on the sonar and the towing direction could be adjusted to get the school between the doors.

The sonar recordings were analyzed by 10 second interval, still picture playback which enabled drawing of the positions and movements of vessel, school and gear on transparent sheets laid directly on the monitor screen. Direction of bearing (ß), horizontal distance from vessel to school (R) and school depth were noted for each interval. Horizontal swimming speed (Vh), radial swimming speed (the speed component,Vr, along the direction of bearing), radial swimming direction (the swimming direction, , relative to the bearing) in addition to vertical swimming speed (Vv) were calculated as described by Misund (1990). According to the mode of vessel operation the observations were categorized as:

- vessel cruising
- pelagic trawling, school in front of vessel
- pelagic trawling, school behind vessel

In cases when the vessel was aiming directly towards a school observed on the sonar, the school was classified as "recorded" if it was recorded by the hull mounted echo sounder or "missed" if it was not recorded. "Missed" schools were further classified as:

- avoided, when they seemed to avoid horizontally
- surface (in echo sounder blind zone), when school depth estimated by the sonar was less than 20 m
- random, when the schools were small compared to the "manouvering presicion".

The observations were further divided in sub-categories according to the prevailing sonar conditions as:

- very bad : school detection range < 400 m
- bad : 400m < school detection range < 700 m
- good : 700m < school detection range < 1000 m
- very good: school detection range > 1000 m

Pelagic trawling as described previously or in some cases bottom trawling were carried out regularly to sample recorded schools. Among other parametres, the length down to the nearest 0.5 cm was measured from about 100 specimens.

RESULTS

Generally, the prevailing sonar conditions and length of the schooling herring and sprat had significant effects on both horizontal, radial and vertical swimming speed (Table 2-4). The horizontal speed increased with fish size up to a length of about 20 cm (Fig. 2), and seemed to decline the better the sonar conditions (Table 5). Similarly there is a weak tendency towards diving (negative vertical swimming speed) as the sonar conditions improve. No systematic influence of sonar conditions on radial swimming speed is indicated as is the case also with fish length on both radial and vertical swimming speed (Fig. 2). The significant species difference in horizontal swimming speed (Table 2) is probably caused by the length difference between the recorded herring and sprat.

The different modes of vessel operation had no specific effects on horizontal or vertical swimming speed of herring, but the radial speed increased during trawling, especially when observed behind the vessel and related to the trawl (Tables 2,4 and 5). This tendency was opposite for the few sprat observations; highest horizontal and radial swimming speed in front of the cruising vessel and lower speed behind the vessel when towing the pelagic trawl.

Maximum speed increased significantly (Spearmans rank correlation coefficient, $rs = 0.43$ and level of significance, $p = 0.05$) with fish size (Fig. 4). The highest value observed was 4.8 m/s for 24.8 cm herring. Maximum relative speed, however, declinced significantly ($rs = - 0.60$, $p < 0.05$) from 18.6 bodylenghts/s for 7.3 cm herring to 7.7 bodylenghts/s for 29.3 cm herring.

The horizontal swimming speed increased significantly both with distance, direction of bearing and depth of the schools (Tables 2-6). The vertical speed declined (indicating more diving) with the depth of the schools (Tables 4-6). In a few occasions the echo sounder showed a cloud, probably caused by released swimbladder gas, on the top of the school. A general impression of schools beeing hearded in front of the approaching vessel, both when cruising and pelagic trawling (Fig. 3,4), is expressed in distinct, nonrandom distributions of radial swimming direction (Fig.5). A similar tendency, but with a clear starboard preferency is present for radial swimming direction behind the vessel and related to the trawl (Fig.5). The three distributions of radial swimming directions were significantly different ($p < 0.05$, Chi-square test), also just the two distributions in front of the vessel ($p < 0.05$), and the two pelagic trawling distributions ($p < 0.05$). A trimodal appearence with greater frequencies around the average angle or 90^0 to both sides is nevertheless present in all three distributions. This indicates that the schools are guided both in front of the approaching vessel and in front of the gear.

The swimming behaviour closer than about 50 m from the vessel is, however, not observed due to the blind zone of the sonar. About 35 % of schools aimed at with the vessel were not recorded on the echo sounder. This proportion of missed schools varied with fish size from about 49 % for medium sized herring (22.5 cm) to 5 % only for the largest herring (Fig. 6a). Splitting the proportion of missed schools into causation-categories revealed that about 13 % of the schools avoided, 14 % were in upper blind zone, and about 8 % were randomly missed. The proportion in each category seemed to vary between size groups (Figure 6b).

Attaching bouyes to the wings to keep the trawl close to the surface, and steering the trawl out of the propeller wake (Fig. 3) clearly increased both the catch rates and the frequency of successful hauls both for herring and mackerel (Table 7).

Figure 7 shows the observations from the midwater or close to bottom hauls. Only in 13 of 39 pelagic trawl trials the schools recorded on the hull mounted transducer were also recorded on the net sonde (Fig. 7). 12 of these schools migrated downwards (20 m in average) during the period between passage of vessel and passage of trawl. 11 of the schools recorded on the net sonde were in contact with bottom. The vertical extension of the schools decreased from an average of 26.6 m when recorded on the hull mounted sounder to an average of 10.8 m when recorded on the net sonde. Five of the trials were successful. The trawl had to be kept very close to the bottom to obtain catches (Fig. 4).

DISCUSSION

The average swimming speed recordings are within the range of both theoretical considerations (Sundnes 1963), and endurance speed measurements of herring in experimental and capture situations (He and Wardle 1988, Misund 1990 a, Blaxter 1969). A decline in relative average speed with increasing fish size is due to a decrease in the tailbeat frequency for larger fish (Wardle 1975). The length dependency is also a probable explanation for the observed species difference in swimming speed as herring and sprat schools seem to have a rather similar swimming pattern in the vicinity of a vessel (Misund 1990 b).

The radial horizontal swimming speed was generally above zero indicating a general horizontal avoidance from the vessel. The vertical swimming speed was, however, generally not different from zero, which means no obvious vertical avoidance within the observation ranges. There were differences between length groups both for radial and vertical swimming speed, but there were no general tendency of length dependence. A maximum speed estimate of 24.1 bodylengths/s for 16.8 cm herring is probably caused by measurement errors, as maximum burst speed of herring is claimed to be around 18 bodylengths/s (Wardle 1977).

The observed variations in maximum school detection range are caused by variations in sonar conditions; Vertical physical gradients (especially temperature gradients) cause the sound to deviate from a straight line propagation. Halvorsen (1985) and Smith (1977) show examples of sonar ray trace calculations for different temperature profiles. The present analyses indicates that improved sonar conditions leads to decreased horizontal swimmimg speed and increased downward swimming speed. Improved sonar conditions also means improved conditions for the propagation of noise. According to Rogers and Cox (1988) the significance of underwater sound as a biological stimulus is very dependent on the conditions for sound propagation. At good sonar conditions the fish may become aware of an approaching vessel at a great distance and react quite moderate on a gradually increasing ship noise. Bad sonar conditions during summer is usually caused by negative temperature gradients, which means that the vessel noise will bend downward and the fish might become suddenly aware of the vessel at a shorter distance, and stronger reactions may be elicted. Such sudden reactons may be the cause of the expell of gas from the herring swimbladder as indicated by echo sounder records of a cloud on the top of a few herring schools. Release of gas will give the fish some extra negative bouyancy and faciliate a quick diving of frightened fish as observed for other physostomous species as kokanee and sockey salmon (Harvey et al. 1968).

The swimming behaviour of the schools seems some influenced by whether the vessel was cruising or trawling and whether the observations were made in front of or behind the vessel. Even though a trawling vessel has increased propeller cavitation leading to increased low frequency noise (Chapman and Hawkins 1969), strong avoidance reactions has been observed only at close distance to the vessel and in the area between the vessel and trawl (Ona and Toresen 1988 b, Godø and Ona 1987, Ona and Chruickshank 1986). The present observations during trawling are made in a range interval from 50 to 375 m from the vessel, which means that the area where the vessel induced reactions are likely to be strongest is not covered. In the present study on herring the horizontal and vertical swimming speed seems rather unchanged, while the radial horizontal swimming speed was higher during trawling. For the few sprat schools observed the tendency is opposite. The results on herring indicates a more directed swimming pattern during trawling compared to cruising (Figures 3-5). The Figures indicate hearding both in front of the vessel and in front of the trawl. Figure 5 also shows an assumed noise directivity diagram for the applied vessel. The diagram is based on diagrams reported for a naval vessel (Urick 1967) and for a trawler (Engås et al. 1990). The herring and sprat are able to detect the direction of low frequency sound (Blaxter 1985, Hawkins 1986, Popper et al. 1988, Fay 1988) and tend to react by swimming away from the source. The observed hearding in front of the vessel implies that the fish senses an increased sound intensity when coming into the main lobes of the vessel noise and react by swimming towards the path of the vessel where the noise intensity is lower. The typical pattern observed in front of the vessel was a forward-sideways-forward swimming, which is a quite reasonable behaviour if the purpose is to keep itself in the minimum sound intensity sector in front of the vessel.

Surprisingly the schools observed between vessel and trawl were heading along with the vessel, and with a clear starbord preferency. According to a trawler noise avoidance model, the fish should be swimming radially away from the vessel (Ona 1989). In the present study fish observed between vessel and trawl seem to respond stronger to stimuli from the trawl than to the noise from the vessel, which in this position is decreasing.

The audible noise from a midwater trawl is probably so weak that it is likely to be masked by the vessel noise. Vibrations in different parts of the gear may generate very low frequency sound. Herring clearly detects and shows startle responses to very low frequencies (Blaxter and Batty 1985, Blaxter and Hoss 1981, Blaxter et al. 1981). However, sensing of such vibrations is probably limitted to the nearfield since it depends on a functional acoustico-lateralis system (Blaxter 1988), and since the ambient noise level is rather high at very low frequencies (Urick 1967). Sand and Karlsen (1988) has, however, shown that cod is quite sensitive to stimuli in the infrasound region and this may also be the case for clupeoids.

Is the observationts between vessel and trawl made when the fish is in visual contact with the trawl ? The bulk of these observations were made at a range of 100-150 m ahead of the trawl, which was the area just in front of and between the doors. As the maximum visual range underwater is assumed to be about 40 m (Tyler 1967), this excludes vision of the trawl itself. Bearing in mind that each school has some horizontal extent and that the reactions of the individuals at the edges may be quickly transferred to the rest of the school (Pitcher 1986, Magurran and Higham 1987), it is likely that the fish were visually orienting relative to the warps, doors and bridles. Due to a slight starboard turn of the vessel during most observations, these parts of the gear tended to approach the schools from the port side. In accordance with a model of visual orientation towards a trawl (Wardle 1986), this may explain the starboard preferency in the swimming directions of the schools (Figure 5).

The observed diving and vertical compression of midwater schools in the period between passage of the vessel and passage of the trawl is in accordance with Taylor (1968). One of the 13 schools observed did, however, show a slight upward movement (Fig. 7). This indicates that the behaviour of the schools may be influenced by other stimuli which sometimes are stronger than those emmitted from the vessel.

The modified technique for trawling close to surface increased the catch rates markedly both for herring and mackerel, and the frequency of successful hauls increased from 46 % to above 80 %. A similar technique has been successfully applied, especially at night, by the Swedish FRV "Argos" and the Danish FRV "Dana". The technique takes advantage of the hearding of schools by the vessel. The schools are not passed over by the vessel to prevent downward avoidance or sideward avoidance to the opposite side of the vessel. The large bouys are important for allowing enough warp length to have the trawl aside the wake of the vessel and to have a proper wing spreading. Similar principles are the basis for the design of a new sampling trawl for juvenile fish (Ona 1989). With this rigging the doors seem to go deeper than the trawl, thereby frightening fish upward towards the trawl. Remarkably few schools were recorded below the footrope during near surface trawling, while it frequently happened during midwater trawling.

Most of the surface trawl hauls gave a mixture of herring and mackerel, but none of the schools recorded on the sonar or the echo sounder were prooved to be pure mackerel schools. This may indicate that the mackerel during this time of the year do not form large schools. The surveys were made towards the end of the spawning season (Iversen et al. 1989). Magnusson and Prescott (1966) reports that other scombrides swim in pairs during spawning.

The preceeding discussion shows that the swimming behaviour of schools when influenced by vessel noise may be more complex than predicted by the model presented by Olsen et al. (1983 b). Tendencies of increasing swimming speed at increasing horizontal distance contradicts this model. These observations might, however, be influenced by positioning errors which increases with the range setting on the sonar. Another contradiction relative to to model was that the deepest schools seemed to have stronger avoidance both horizontally and vertically compared to shallower schools. Downward avoidance is a common flight response of herring (Blaxter 1985), and the possibility exists that the deepest schools are deepest because they have just been scared by a predator or a vessel. If the individuals in these schools still were quite alert as our vessel approached, this may explain why these schools were the most avoiding. Another possibility is that the sound propagation conditions leads to an increased vessel noise with depth at some distance from the vessel. The typical summer condition in this area is that the sound bend downward, as illustrated by Halvorsen (1985).

Despite the discussed guiding effect of the vessel, 35 % of the schools aimed at were not recorded on the hull mounted echo sounder. This strongly indicates that significant avoidance occurs at ranges less than 50 m were there are no sonar observations. Tentative estimates of 14 % missed due to echo sounder blind zone and 8 % "randomly" missed, leaves 13 % of the schools at sufficient depth missed due to avoidance. The split of missed schools is, however, rather uncertain. Schools estimated to be at depths less than 20 m on the sonar were considered to stay in echo sounder blind zone, while the true blind zone was only 8 m. The reason for this choise is that the depth measurments by sonar is quite uncertain at low tilt angles (Misund 1990); A school staying at 8 m depth will be estimated to stay at 20 m if observed at 200 m range with -6^0 tilt.

One could expect that the general tendency of increased swimming speed with fish length should lead to an increased proportion of avoiding schools with increasing length. Other variable factors not taken account of may be the reason why this was not observed (Fig. 6).

The conclusion is that some 30 % of the schools observed on the course line of the ship 50-350 m ahead of the vessel was missed by the echo integration system, mainly due to avoidance and upper blind zone. Even if the fish was influenced by the vessel already when observed on the sonar, this gives some order of magnitude for the bias of the echo integrator estimates derived from these particular surveys (Kirkegaard et al. 1989, Kirkegaard et al. 1990). This illustrates the needs for applying multibeam sonar for school size measurements and school counting (Misund et al. 1990, Misund et al. 1989) as a supplement to conventional echo integration.

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Table 1 Number of video recorded schools at different vessel operation modes and number of midwater schools aimed at and recorded during pelagic trawling.

S = Number aimed at from sonar records
S+ES = Number recorded both on sonar and echo sounder
S+ES+NS = Number recorded both on sonar, echo sounder and net sonde.

	Number of video recorded schools				Number of midwater schools aimed at and recorded		
YEAR	Cruising	Pelagic trawling					
		In front of vessel	Behind vessel		Aimed at (S)	S+ ES	S+ ES+NS
			Mid-water	Near surface			
1988	132	-	4	-	22	9	7
1989	92	24	5	8	17	7	6
Total	224	24	9	8	39	16	13

Table 2 Nested linear model with distance, bearing and depth as continous effects using horizontal swimming speed as dependent variable.

	d.f.	Mean Square	F-value	p	r^2
Model	35	2.36	4.84	<0.001	0.15
Source					
Species	1	1.54	3.15	0.076	
Mode (species)	3	0.61	1.26	0.288	
Sonar (species mode)	6	2.04	4.18	<0.001	
Length (species mode sonar)	22	2.17	4.46	<0.001	
Distance	1	13.27	27.22	<0.001	
Bearing	1	2.06	4.23	0.040	
Depth	1	3.90	8.00	0.004	

Table 3 Nested linear model with distance, bearing and depth as continous effects using radial swimming speed as dependent variable.

	d.f.	Mean Square	F-value	p	r^2
Model	35	1.61	2.90	<0.001	0.09
Source					
Species	1	0.95	1.71	0.191	
Mode (species)	3	4.03	7.25	<0.001	
Sonar (species mode)	6	2.63	4.73	<0.001	
Length (species mode sonar)	22	1.05	1.89	0.007	
Distance	1	1.75	3.15	0.076	
Bearing	1	1.39	2.49	0.114	
Depth	1	1.32	2.37	0.124	

Table 4 Nested linear model with distance, bearing and depth as continous effects using vertical speed as dependent variable

	d.f.	Mean Square	F-value	p	r^2
Model	35	2.30	4.03	<0.001	0.12
Source					
Species	1	2.26	3.96	0.046	
Mode (species)	3	0.34	0.59	0.620	
Sonar (species mode)	6	0.43	0.76	0.600	
Length (species mode sonar)	22	0.79	1.38	0.114	
Distance	1	2.20	3.87	0.049	
Bearing	1	1.69	2.96	0.085	
Depth	1	53.35	93.70	<0.001	

Table 5 Swimming speed durig different modes of vessel operation, positions relative to vessel and sonar conditions (IFV:school in front of vessel. BV:school behind vessel, X:average, SD:standard deviation, N:No of measurements, S:p<0.05, NS:p>0.005).

Species	Vessel Mode	School Position	Sonar Condition	Swimming speed (m/s)							
				Horizontal		Radial			Vertical		
				X	SD	X	SD	N	X	SD	N
Herring	Cruising	IFV		1.06	0.74	0.22	0.77	831	-0.01	0.78	953
	Trawling	IFV		1.06	0.78	0.46	0.71	157	0.06	0.53	160
	Trawling	BV		1.01	0.67	0.58*	0.75	93	0.04	0.91	55
Sprat	Cruising	IFV		0.94	0.53	0.56	0.67	34	-0.27	1.04	32
	Trawling	IFV		-	-	-	-	-	-	-	-
	Trawling	BV		0.51	0.45	0.01*	0.37	35	-0.20	0.59	13
Herring & sprat	Cruising & Trawling	IFV	Very Bad	1.10	0.77	0.19	0.88	55	0.11	0.50	55
		IFV	Bad	1.21	0.83	0.30	0.88	232	0.02	0.71	275
		IFV	Good	1.00	0.70	0.31	0.73	569	-0.01	0.84	584
		IFV	Very Good	0.94	0.70	0.24	0.68	295	-0.06	0.71	300

* Radial speed relative to the trawl

Table 6 Horizontal, radial and vertical swimming speed rank correlated to distance, bearing and depth of the schools (rs: Spearmans rank correlation coefficient, p: level of significance, S: p<0.05, NS: p>0.05).

	Distance			Bearing			Depth		
	rs	p	N	rs	p	N	rs	p	N
Horizontal speed	0.19	S	1137	0.15	S	1151	0.17	S	1047
Radial speed	0.01	NS	1137	0.06	NS	1151	0.08	S	1047
Vertical speed	0.08	S	1201	0.04	NS	1045	0.23	S	1214

Table 7 Average catch rates (kg per hour) in pelagic trawl close to surface (depth of headline less than 50 m) with ordinary rigging and with bouyes attached to the headline.

	Herring			Mackerel		
	Ordinary rigging	Bouyes attached	Wilcoxon test (p)	Ordinary rigging	Bouyes attached	Wilcoxon test (p)
Catch rate	191	456	0.012	9	47	0.009
St. Dev.	454	1001		18	71	
No. of hauls	13	37		13	37	
Frequency of zero catch (%)	54	11		54	19	

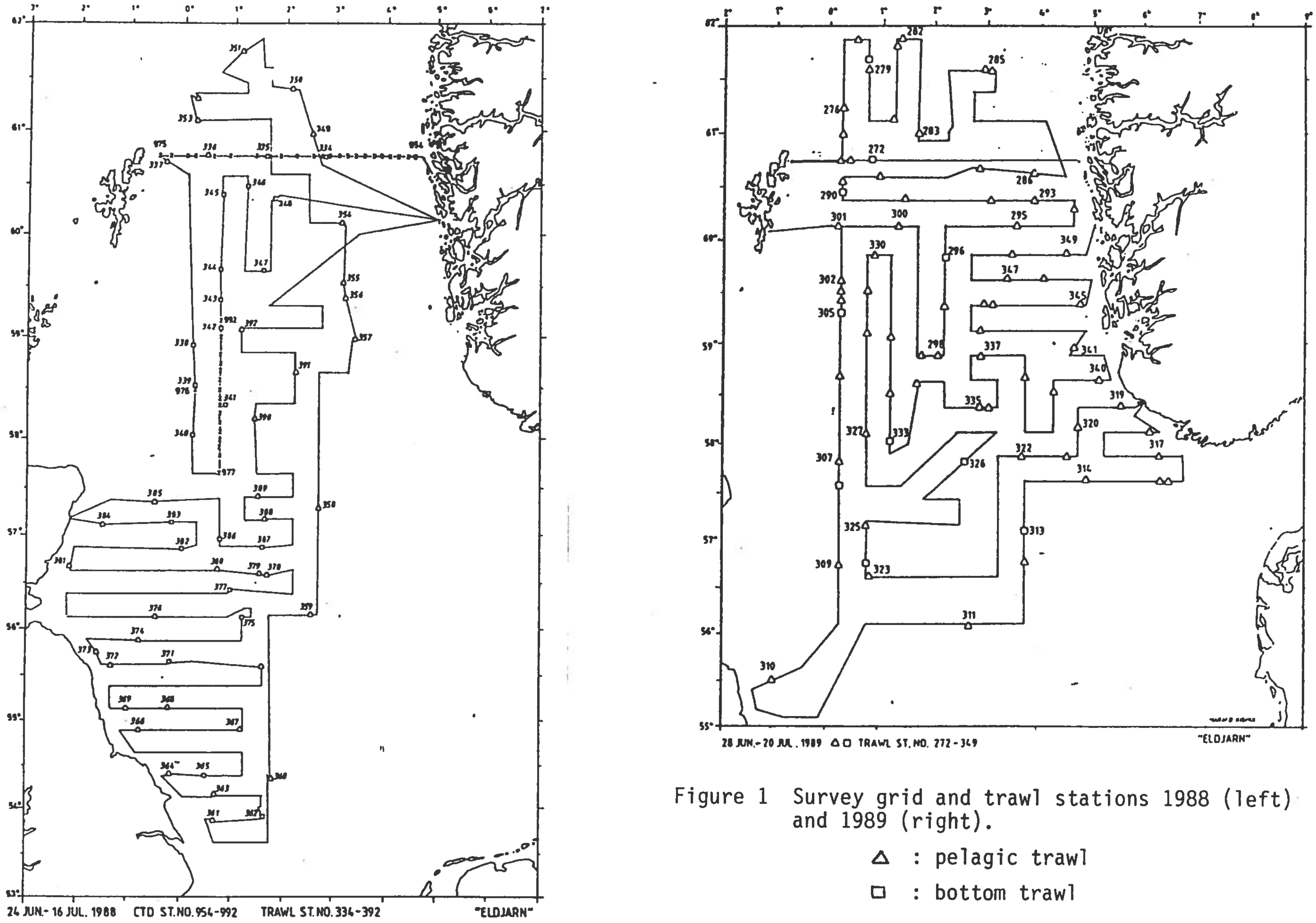


Figure 1 Survey grid and trawl stations 1988 (left) and 1989 (right).

△ : pelagic trawl

□ : bottom trawl

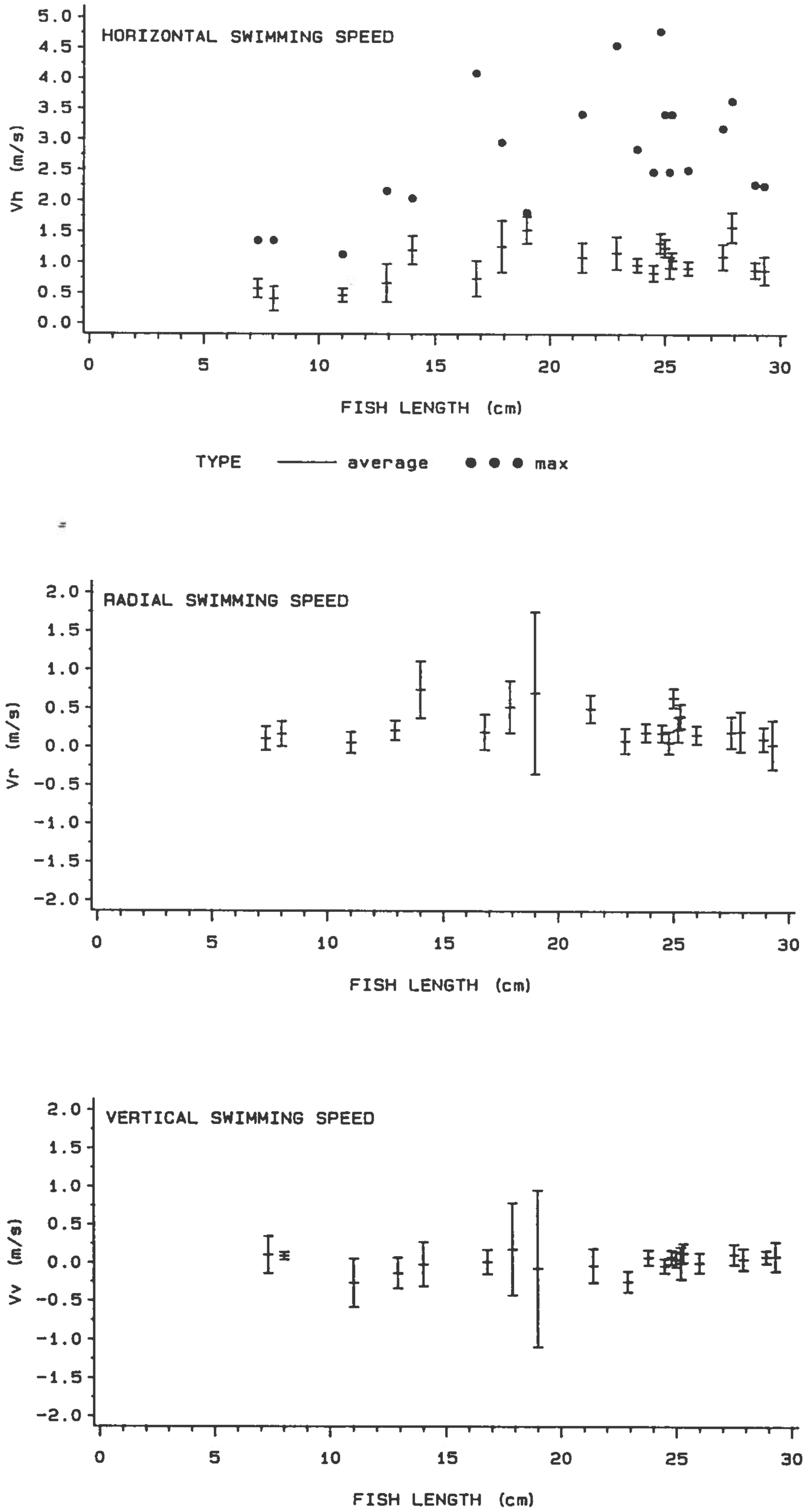


Figure 2 Estimated swimming speed versus fish length.

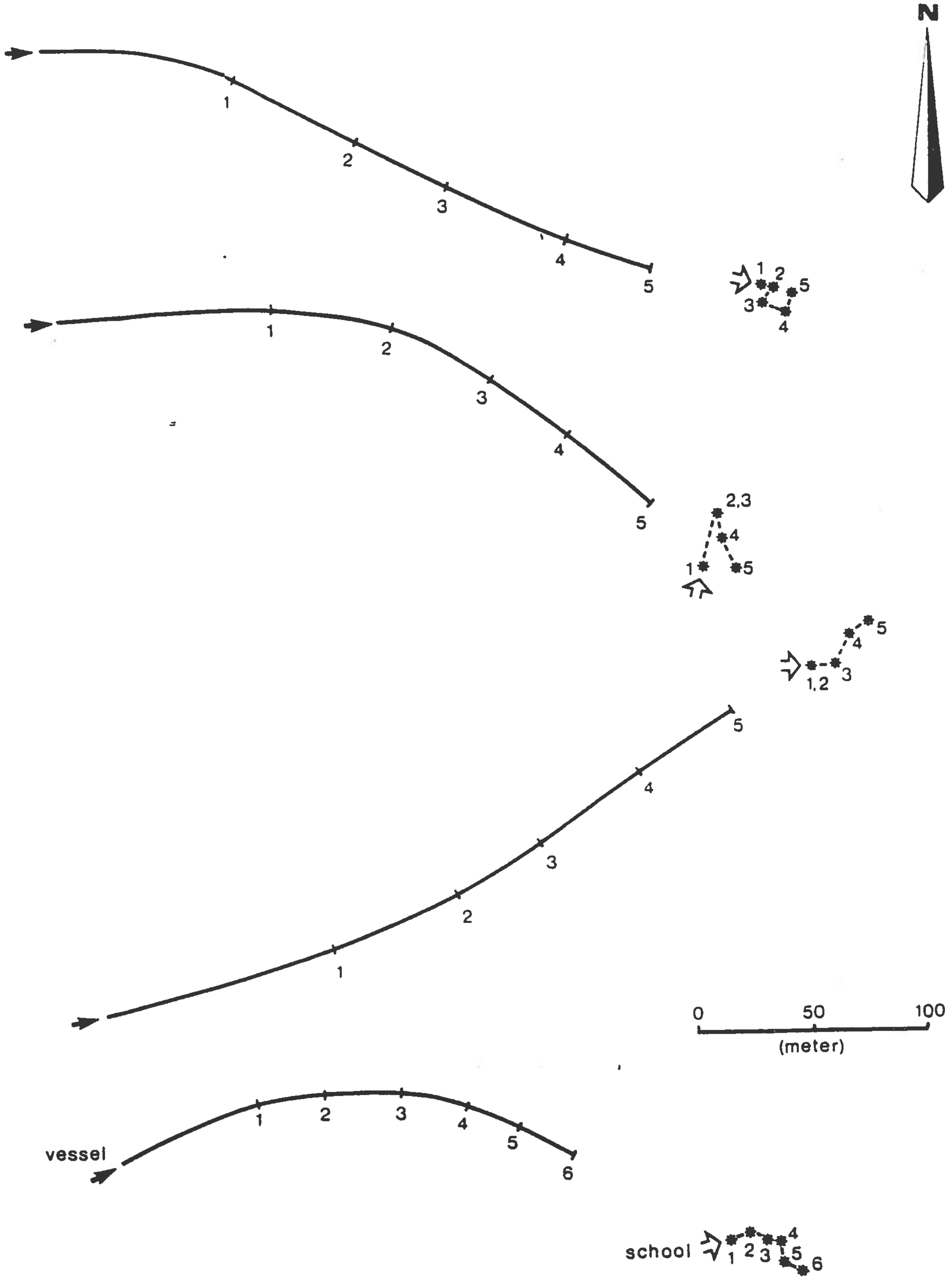


Figure 3a Position tracks of vessel and schools when cruising towards four different schools. The time interval between successive positions is 10 seconds.

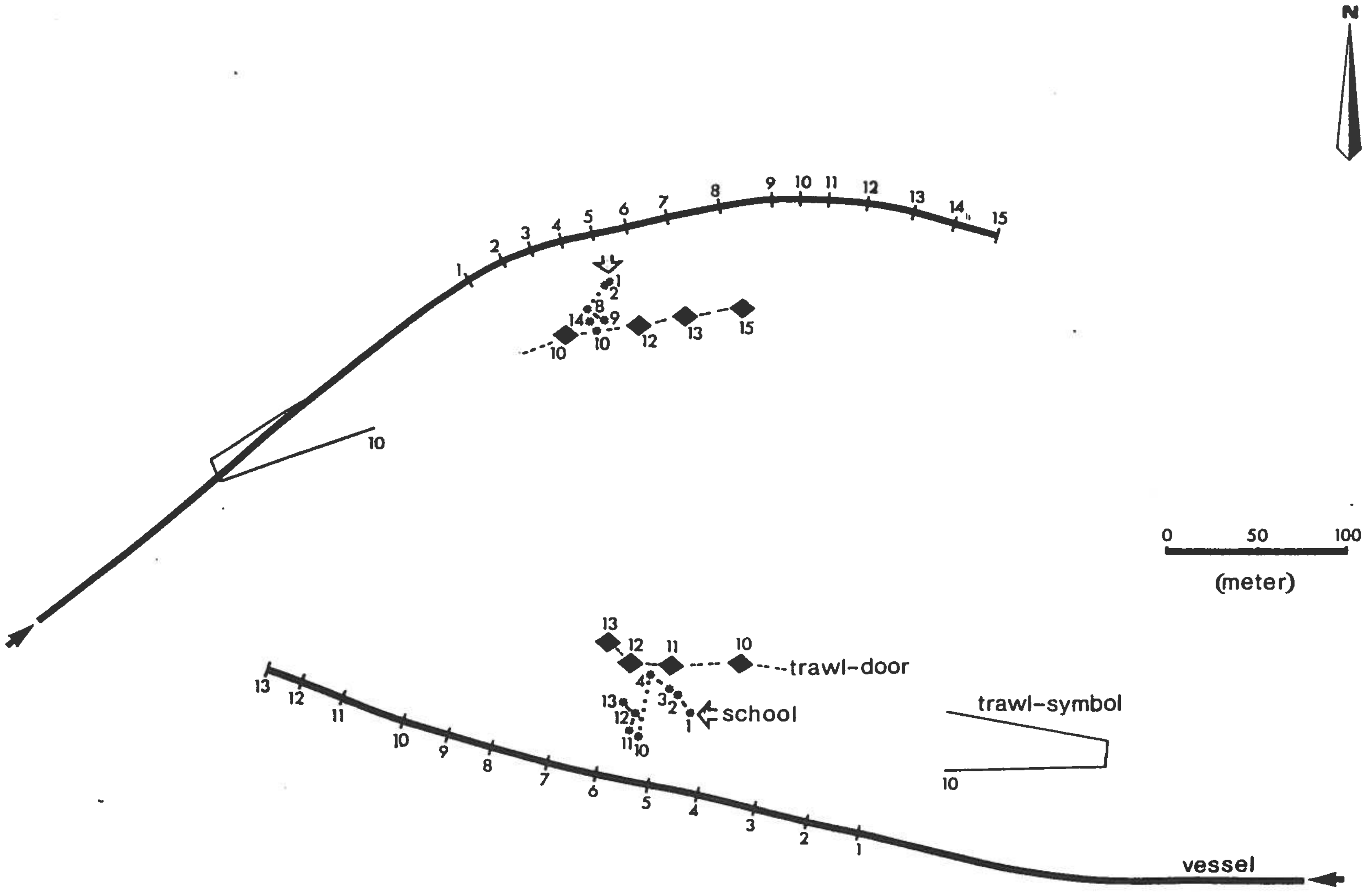


Figure 3b Position tracks of vessel,schools and starboard trawl door. The tracks show the typical manouvering pattern when trawling near surface with bouys on the trawl. The time interval between successive positions is 10 seconds.

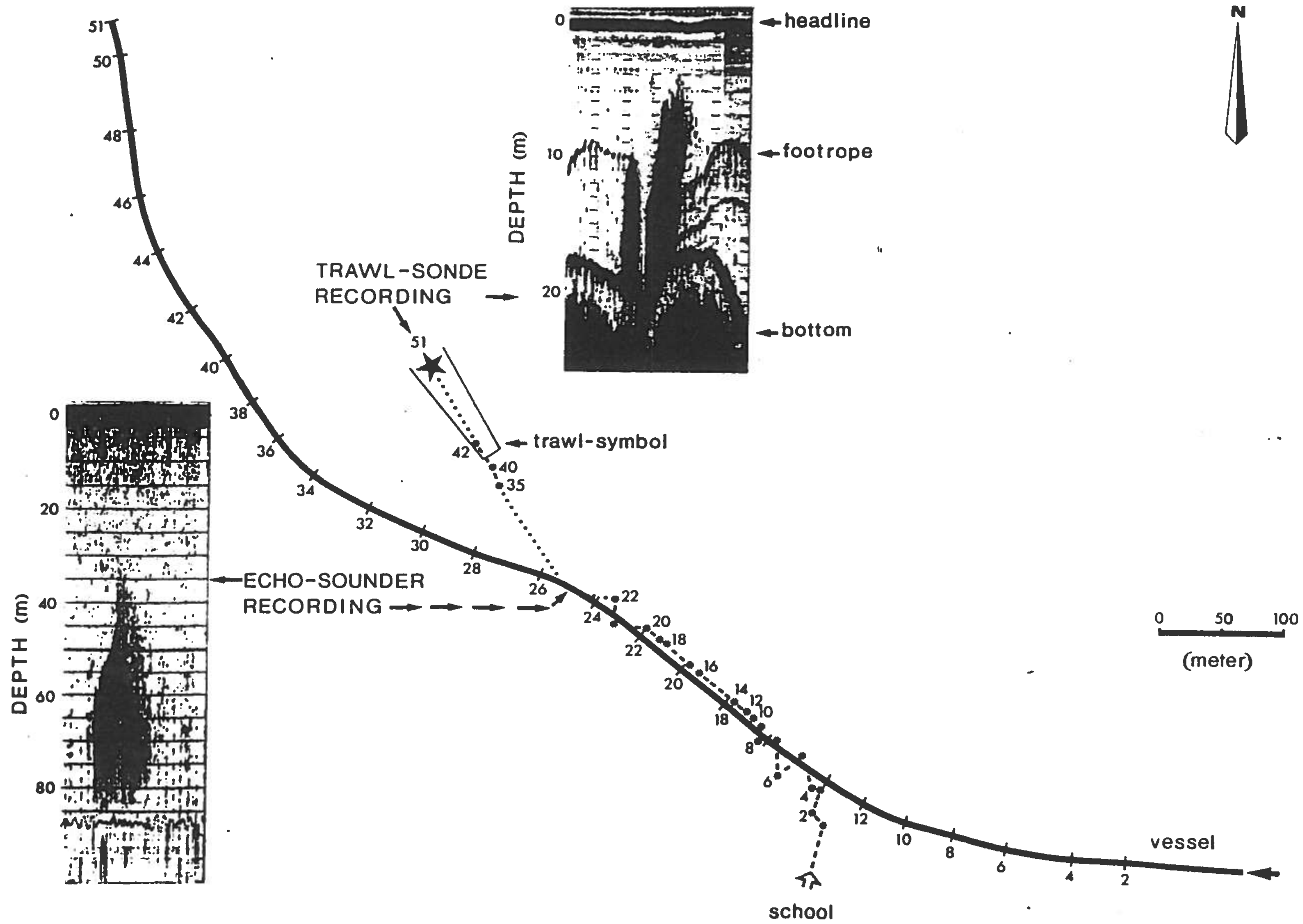


Figure 4 Position track of the vessel and a midwater school showing particular strong avoidance during pelagic trawling. The interval between successive positions is 10 seconds. The records from hull mounted echo sounder (time interval 26) and net sonde (time interval 51) show a compression and vertical movement of the school.

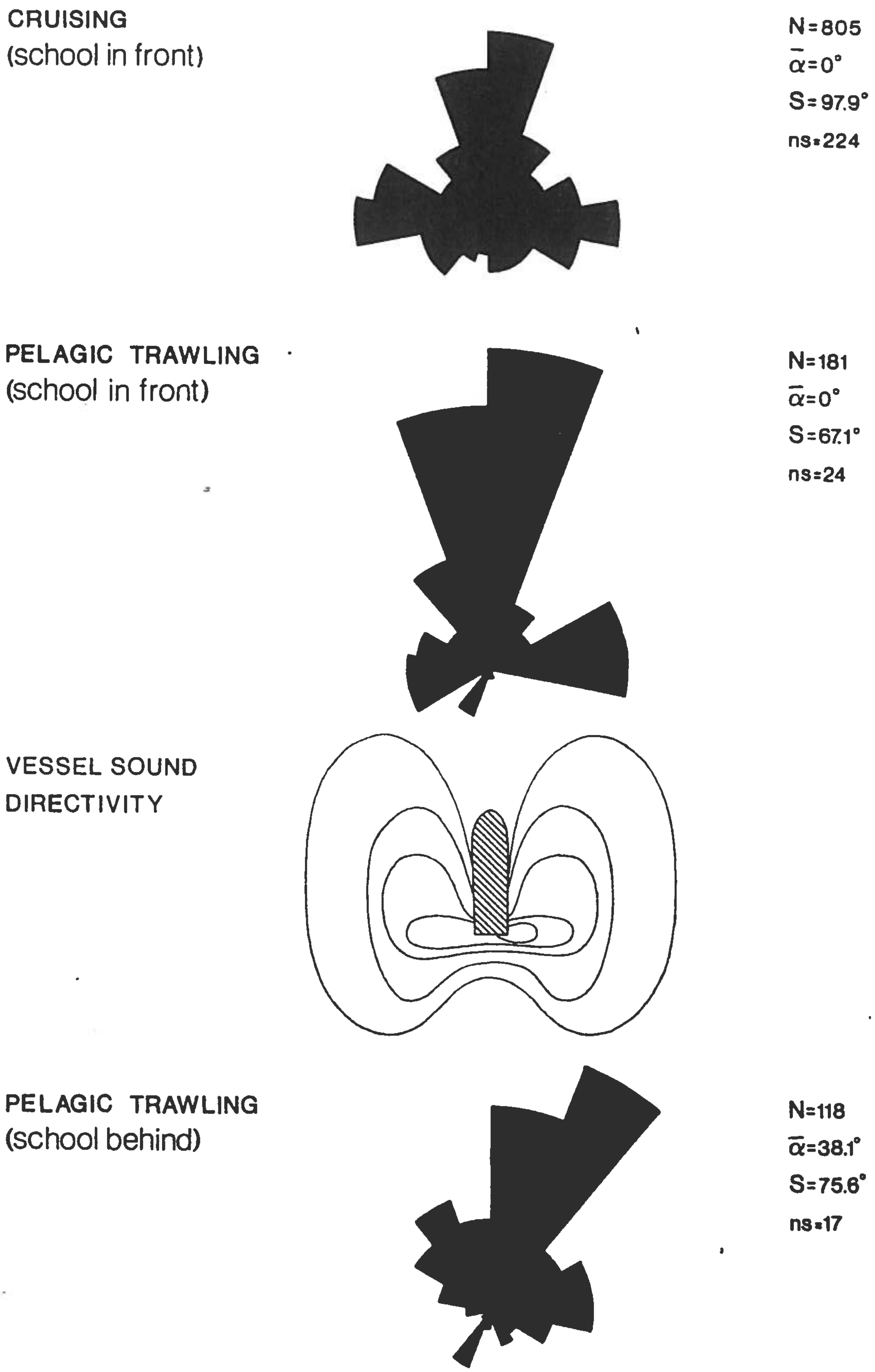
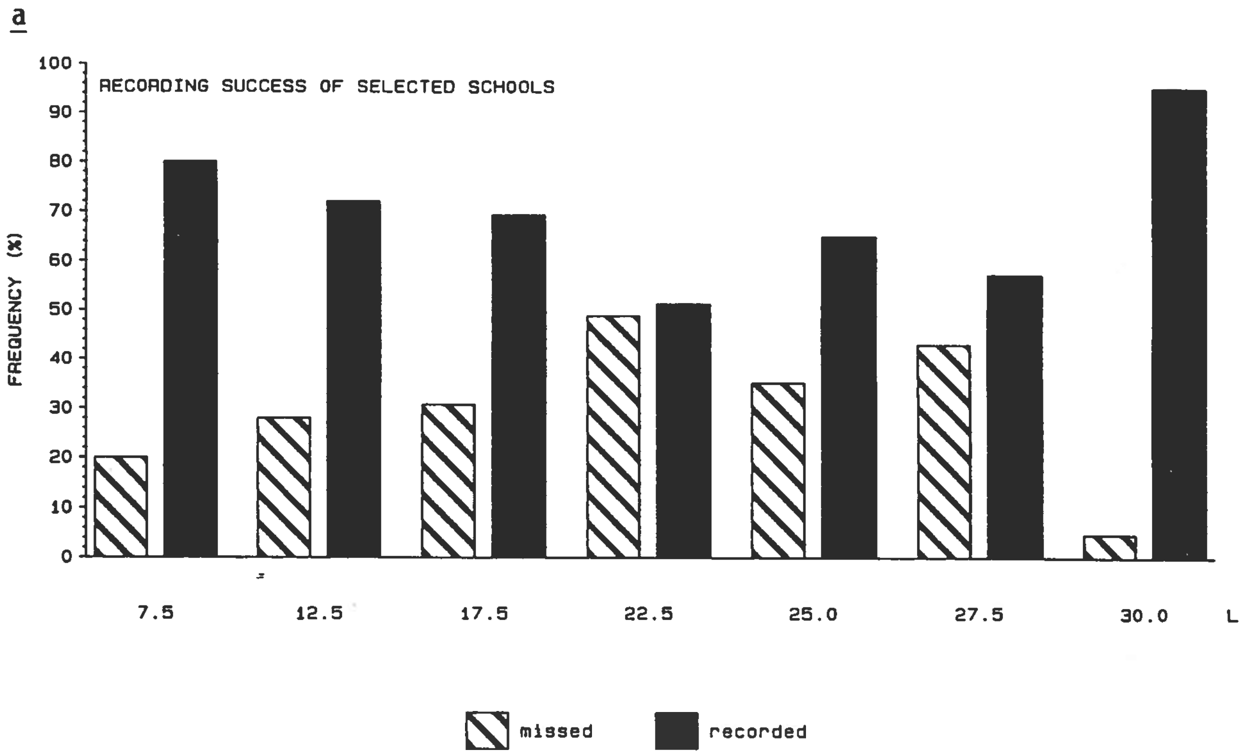


Figure 5 Distributions of "radial swimming directions" (α), and a presumed noise directivity diagram of the vessel. The distributions labeled "school in front" represents swimming directions relative to the radial direcion away from vessel. The distribution labeled "school behind" shows the swimming directions relative to the radial direction away from the trawl. **N**= number of observations, $\bar{\alpha}$= mean angle, S= angular standard deviation, ns= number of schools.



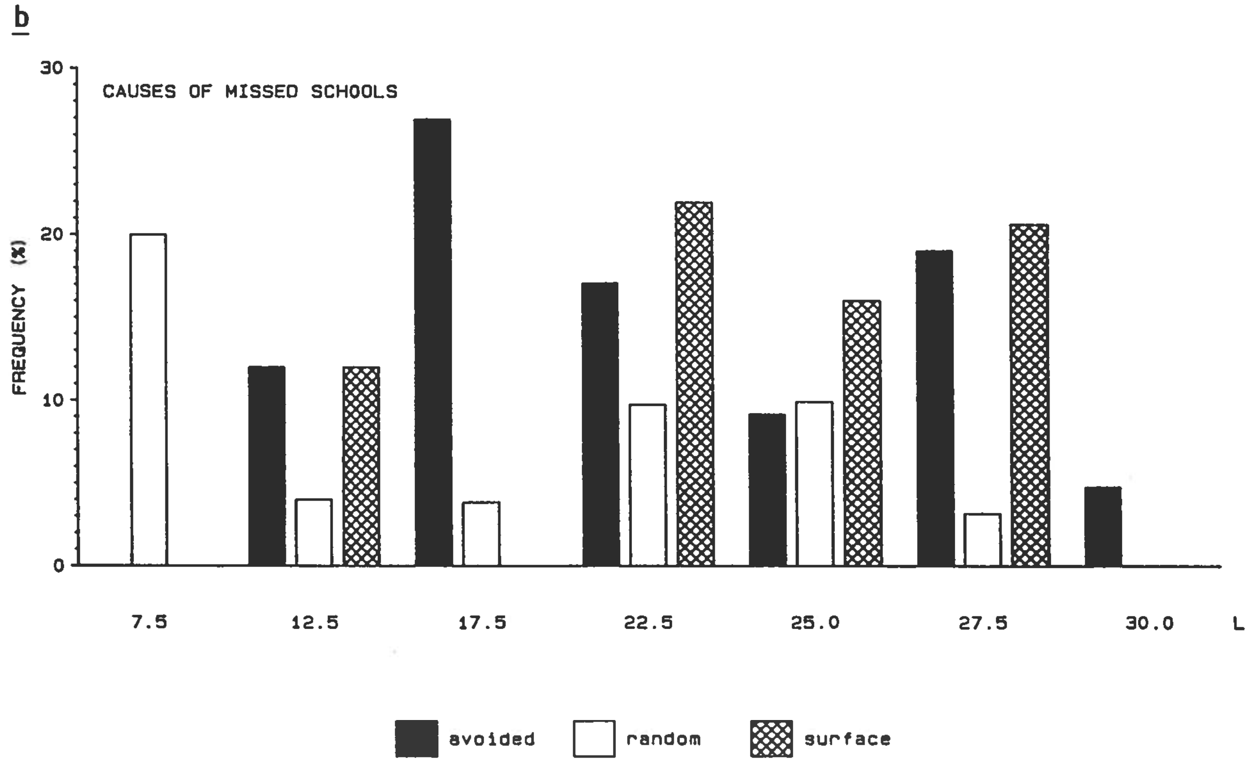


Figure 6 a : Pecentage of schools missed on echo sounder versus fish length.

b : Percentage of schools missed due to avoidance, unprecise navigation (random) and echo sounder blind zone (surface) versus fish length.

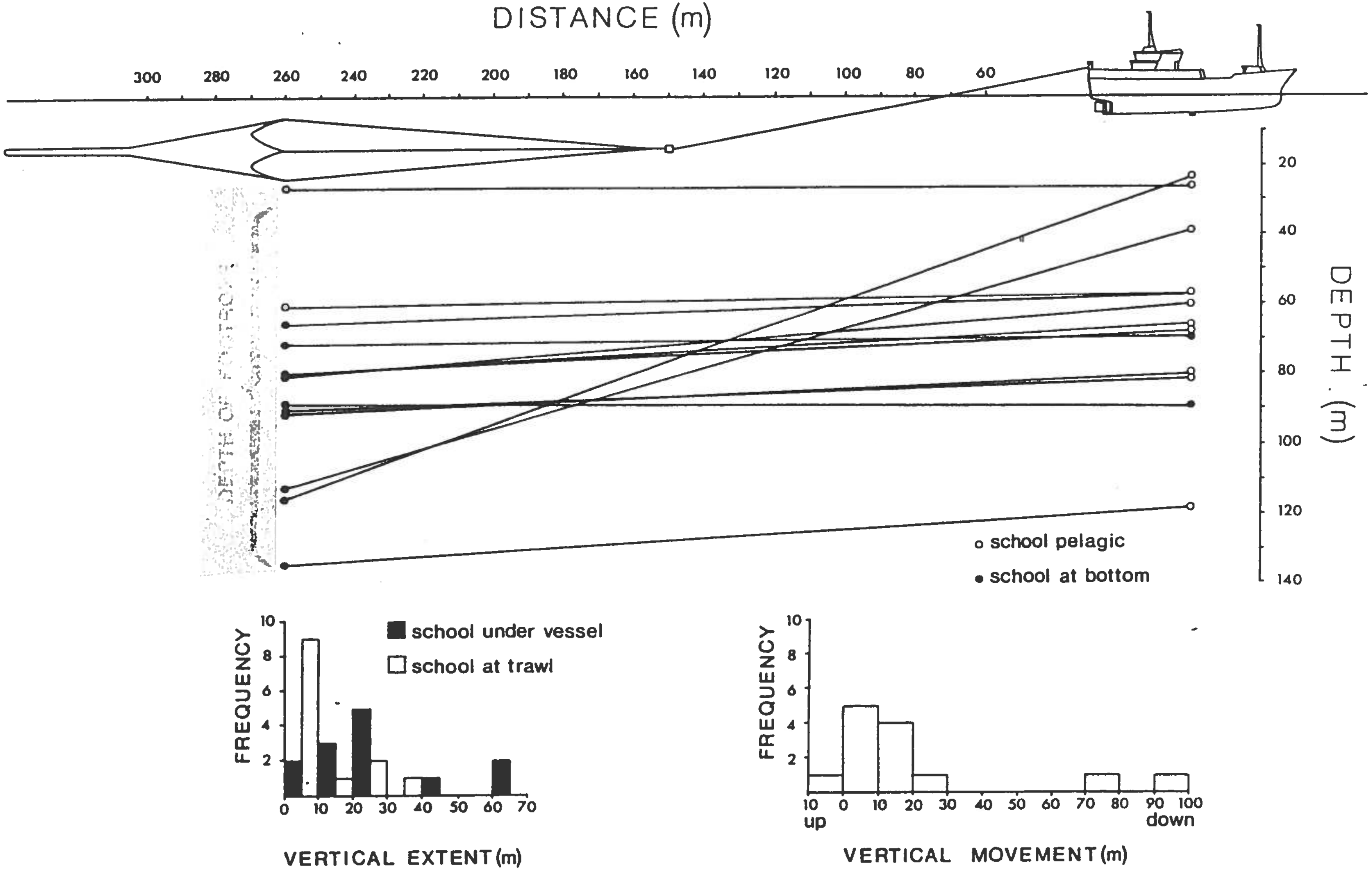


Figure 7 Upper : Depth of schools observed underneath vessel and underneath trawl. Vessel and trawl are drawn to show the horizontal dimensions. The depth of the trawl was usually kept near the school depth recorded beneath the vessel.

Lower left: Vertical extent of schools underneath vessel and trawl.

Lower right: Frequency distribution of vertical movement of schools.