

**MAPPING THE MIGRATION PATTERN OF SCHOOLING FISH
BY USE OF MULTI-BEAM SONAR
DURING CONVENTIONAL ACOUSTIC SURVEYS**

by

M. T. Hafsteinsson¹ and O. A. Misund²

¹Department of Fisheries and Marine Biology, University of Bergen, N-5020
(present address: Norwegian College of Fisheries Science, N-9037 Tromsø, Norway)

²Institute of Marine Research, P. O. Box 1870, N-5024 Bergen Norway

ABSTRACT

Information on migration pattern and swimming behaviour of pelagic fish schools in the vicinity of steaming survey vessels has been collected by a multi-beam sonar system connected to an external device for data collection during three conventional acoustic surveys. Two cruises were conducted on herring in the North Sea in July 1991 and 1992, and the third one on capelin in the Barents Sea in January 1992. A method for graphic presentation of swimming tracks of recorded schools was established for analysis of the behavioural pattern of the schools. Based on such swimming tracks, schools were categorized by pre-defined criteria as migrating, vessel avoiding or undetermined. Estimates of the vessel avoidance frequency, swimming speed, the migration direction, and the migration speed and depth of the schools, have been obtained. During both North Sea surveys, the majority of observed herring schools were migrating south. The average migration of the capelin was northwards. Mean swimming speeds of herring schools were in accordance, both with theoretical considerations as well as results of earlier sonar studies conducted under similar conditions in the North Sea. The validity of estimated swimming speeds of capelin was more uncertain, as the swimming capacity of that species is not well known.

Key words: Acoustic survey, Multi-beam sonar, Avoidance, Swimming speed, Migration speed, -direction and depth.

Introduction

Knowledge of behaviour and migration patterns of fish is of major interest for survey planning and execution, as well as for the interpretation of data for acoustic stock assessment of pelagic fish. Such information is essential for survey design, and successful surveys are dependent on choosing a favourable survey time when the target stock is available within an area accessible to survey vessels (Simmonds *et al.*, 1991; Gunderson, 1993).

Active migration of a fish population during a survey may influence the estimation of the distribution area of the fish (MacLennan and Simmonds, 1992). If the fish is migrating in the same direction as the survey is progressing, the distribution area may be overestimated. Conversely, if the fish is migrating against the direction the survey is progressing, the distribution area of the fish may be underestimated.

Research on avoidance behaviour done with multi-beam true motion sonars has opened possibilities for a more extensive description and quantification of schooling behaviour (including horizontal avoidance) in the vicinity of vessels (Aglen, 1985; Misund, 1990; Misund and Aglen, 1992). By systematic collection of sonar data the reliability of acoustic fish density estimates can be assessed (Misund *et al.*, 1993).

The aim of this study was to observe the migration behaviour of pelagic fish schools with sonars during acoustic surveys. This required evaluation of the frequency of influence (avoidance/disturbed swimming behaviour) of research vessels on the swimming behaviour of encountered schools. For this purpose a methodology has been developed to categorize the swimming behaviour of recorded schools as migration, vessel avoidance or undetermined. We then calculate;

- i mean swimming speeds and depths of migrating fish schools in the area.
- ii the direction and speed of migration of fish schools in the survey area, and the main heading of migration of a population as observed during the survey period.

Material and methods

The material for this study was collected during three acoustic surveys (Table 1). The first cruise was undertaken in the northern North Sea in 1991 as a part of the ICES coordinated acoustic herring (*Clupea harengus*) surveys conducted in July each year (Bailey and Simmonds, 1990; Anon, 1992). Cruise number two was an experimental cruise conducted in the North Sea primarily to test a new sonar system installed onboard the RV "G. O. Sars" (Aglen, 1993). The survey area was located over the western slope of the Norwegian trench and material was collected on herring schools. Cruise lines were followed in a zig zag manner extending from north to south-east along the slope. The southern part of the grid lines was traversed repeatedly

northwards again for a second covering of this area. The purpose of this was to investigate possible changes in swimming behaviour of schools between replicated surveys conducted in the same area near in time. The third cruise was a conventional survey executed annually in January where the main purpose is to map the distribution and assess the abundance of the capelin (*Mallotus villosus*) stock and juvenile herring in the Barents Sea (Hamre, 1992).

During the surveys sonar data were collected from pelagic schools while the vessel moved at constant heading along pre-planned survey grid lines at a speed of about 3.6 - 5.7 m s⁻¹ (7 - 11 knots), and with the sonar systems working in relative mode. Onboard RV "Johan Hjort" a HP 9000/720 workstation was connected to a serial port on the Simrad SR 240 sonar for ping-by-ping logging of telegrams containing data on school position in relation to vessel, swimming speed and depth, and vessel maneuvering. On the RV "G. O. Sars" data on school position in relation to vessel, swimming speed and depth were stored on video tape by a VHS video recorder connected to a video output from the Simrad SA 950 sonar.

The recorded schools were occasionally sampled by pelagic trawls for identification of acoustic registrations. Length (rounded to the nearest 0.5 cm), sex, and stage of maturation was recorded for about 100 specimens from each sample. In Table 2, the total numbers of schools from which swimming data were sampled with descriptive statistics of observation time, are given for each cruise.

It is reasonable to assume that the first ping observations from a school are somewhat more inaccurate regarding registration of school position than later pings, as during the first contacts the target tracking function of the sonar is stabilizing on the density center of the school. School registrations with short recording time (few pings) can therefore be assumed to have a greater amount of error in the registrations than schools with longer time of observation. The quality of the school recordings was therefore evaluated by plotting recorded swimming speed for the herring schools observed in the North Sea in 1991 by the Simrad SR 240 sonar against ping number (Fig. 1). This reveals that the variability in observed swimming speed tends to be highest during the first pings (Fig. 1A). Observed swimming speeds range mostly from about 0 to 4.0 m s⁻¹. Higher values are scarce although some 'jumps' in speed values tend to appear occasionally up to about 180 pings. A tendency for higher swimming speed values during first pings can be seen and this is confirmed in Figure 1B where mean swimming speeds with standard errors have been calculated for each ping number up to 100 pings. The mean swimming speed for each ping increases during the first pings with a peak at about 8-10 pings (approx. 1.9 m s⁻¹), thereafter to decrease and stabilize. After about 60 pings the variability increases and mean values become more unstable. This is however not due to errors in the sonar itself, but because of the effect of relatively few observations with rather high range in swimming speed values in the data (Fig. 1A). It is concluded that those first school observations are somewhat less precise regarding registrations of swimming pattern parameters (speed, direction, depth) than results from later

pings. A total of 17 schools having total observation time shorter than 20 seconds (approx. 20 pings) were therefore considered to give uncertain results and they were excluded from the data.

As the purpose of this study was to quantify the natural migration pattern of schooling fish populations, it was of major importance for the outcome of the analysis that schools showing disturbed swimming behaviour were removed from the data set before further studies on migrating pattern were done. For this purpose it was found necessary to visualize the swimming tracks of the recorded schools during observations.

An algorithm was written in SAS (Anon., 1988) for calculations of school position at every observation. The distance in meters from either side of the boat was found by

$$X = (\sin \alpha) R$$

where α is the bearing from vessel to school, and R is range from vessel to schools in meters. As the vessel moved along it was necessary to correct for the vessel progression in the calculations of school position coordinates ahead or behind vessel. This was done by adding the distance sailed by the vessel from the beginning of the observations to the actual observation. The formula for the Y school coordinate then had the form

$$Y_k = (\cos \alpha R) + \sum_{i=0}^{i=k} \Delta y$$

where

$$\Delta y = tv$$

in which t is the time elapsed in seconds from ping to ping and v is the vessel speed in m s^{-1} .

On the Simrad SA 950 display, speeds of tracked targets are presented as integers. For fish schools, which move relatively slowly the rounded numbers are far too rough expressions for estimation of swimming speed. Therefore, the movement of schools had to be calculated directly based on observed range (R) and bearing (α) from vessel to school as recorded for each sonar observation. School movement related to those positions was found by calculating the difference (distance) between each X and Y coordinates respectively by

$$\Delta X_n = X_n - X_{n-1}$$

and

$$\Delta Y_n = Y_n - Y_{n-1}$$

where X_n and Y_n are school positions at observation n and X_{n-1} and Y_{n-1} are the positions at previous observation. The net movement (ΔZ_n) of the school in meters between each observation could then be calculated by

$$\Delta Z_n = \sqrt{(\Delta X_n)^2 + (\Delta Y_n)^2}$$

Swimming speeds (V_n) in m s^{-1} between each observation were then computed by

$$V_n = \left(\frac{\Delta Z_n}{\Delta t_n} \right)$$

where Δt_n is time elapsed in seconds from observation ($n-1$) to observation (n). To obtain realistic estimates, the swimming speed measurements were averaged over four pings, which corresponds to a time interval of about 10 s (Hafsteinsson 1994).

On the basis of the swimming tracks, the schools were judged as migrating, avoiding, or undetermined (Fig. 2). Those schools that were classified as "undetermined" were impossible to judge, either due to irregular swimming behaviour and little movement during observation, or short observation time. Schools were classified as avoiding when either of the following criteria were met:

- i Sustained swimming course¹ changed more than 45° from the initial direction observed and the school headed away from the vessel. After that it did not change its new swimming course more than 45° . New swimming course was kept until the vessel had passed, or until school disappeared from the sonar.
- ii Sustained swimming course changed more than 45° , towards the path of the vessel. Later the schools could also again change their swimming course in any direction more than 45° .

The schools judged by the first criterion were assumed showing direct horizontal avoidance from the vessel. Schools satisfying the second criterion were thought to be caught between sound

¹Sustained swimming course is here defined as an observed swimming course kept by the school for a time interval over about 10 seconds.

emission lobes of higher sound intensity to the sides of the vessel, and trying to stay in the lower sound intensity field in front of the vessel (Urlick, 1983; Misund, 1990; Misund and Aglen, 1992; Misund *et al.*, 1993).

For the migrating schools, the swimming component in the north (V_N) and east (V_E) direction for each observation was calculated by

$$\begin{aligned} V_{N_{ij}} &= V_{ij} \times \cos(\alpha_{ij}) \\ V_{E_{ij}} &= V_{ij} \times \sin(\alpha_{ij}) \end{aligned}$$

The average migration speed for each school was found by

$$V_{m_j} = \sqrt{\left(\frac{1}{N} \sum_{i=1}^n V_{N_{ij}}\right)^2 + \left(\frac{1}{N} \sum_{i=1}^n V_{E_{ij}}\right)^2}$$

and the average migration direction β_{m_j} for each school by

$$\beta_{m_j} = \arccos\left(\frac{\frac{1}{N} \sum_{i=1}^n V_{N_{ij}}}{V_{m_j}}\right)$$

Similarly, the average migration speed (V_M) for all migrating schools was found by

$$V_M = \frac{1}{M} \sum_{j=1}^M V_{m_j}$$

and the average migration direction β for all migrating schools by

$$\beta = \arccos\left(\frac{\frac{1}{M} \sum_{j=1}^M V_{N_j}}{V_M}\right)$$

For comparison the migration direction (β_c) of each school was calculated by averaging the swimming directions (α_{ij}), according to the method for circular distributions (Zar, 1974). The migration speed (V_{MC}) was then found by

$$V_{Mc} = \frac{1}{N \cdot M} \sum_{j=1}^M \sum_{i=1}^N (V_{ij} * \cos(\alpha_{ij} - \beta_c))$$

Results

About 20% of the North Sea herrings schools were influenced by the vessel in 1991, and about 24% the year after (Table 3). The degree of uncertainty in the observations should however be noted. A total of about 19% of the schools in 1992 were categorized as undetermined. Just two capelin schools seemed to avoid the vessel.

No significant difference could be found between mean swimming speed and depths of the migrating and avoiding schools. Mean swimming speed for the schools recorded in the North Sea in July 1991 was about 1.2 m s⁻¹ (Table 4). Lowest observed mean value for a school was 0.45 m s⁻¹ and the fastest school moved at a mean speed of 2.44 m s⁻¹. Mean swimming depth of the schools was also quite stable at about 30 - 40 m for the whole area surveyed, but the depth of individual schools varied from 4 m and down to about 140 m.

Mean swimming speeds of the herring schools observed in 1992 were much alike the results obtained one year earlier, both when means of all schools are regarded as well as when minimum and maximum values are compared (Table 4). Mean swimming depth was the same for the undisturbed and the disturbed schools (31 m). Similarly, there was no significant difference in average swimming speed between migrating and avoiding schools ($p > 0.05$).

Mean swimming speed for migrating capelin schools was 0.82 m s⁻¹, and the two avoiding schools were swimming at an average speed of about 0.7 m s⁻¹ (Table 4). The capelin schools were swimming at an average depth of about 44 m, but varying from 4 m down to 117 m for the individual school.

Most of the herring schools recorded in the North Sea were migrating southwards during the 1991 and the 1992 surveys (Figs. 3 and 4). Average migration direction for all schools was 194° and 196° for the 1991 and 1992 surveys, respectively (Table 5). The capelin schools in the Barents Sea were swimming in more random directions (Fig. 5), and average migration direction was 2° (Table 5).

The average migration speed for the North Sea herring schools was 0.19 m s⁻¹ in 1991 and 0.52 m s⁻¹ for the schools recorded during the mini-survey in 1992 (Table 5). The capelin schools were migrating northwards at an average speed of just 0.1 m s⁻¹ (Table 5).

The alternative method for calculating migration direction and migration speed gave rather similar results, as the vector component-method. Average migration direction calculated by the method for circular distributions were 200°, 196°, and 349° for the 1991 North Sea herring schools, 1992 North Sea herring schools, and 1992 Barents Sea capelin schools, respectively. The migration speeds calculated by the alternative method were similar to those given in Table 5.

Discussion

Disturbed swimming behaviour

Apparently, the frequency of disturbed swimming pattern for North Sea herring was slightly higher in 1992 (24%) than observed in 1991 (19%). It should, however, be emphasized that the degree of uncertainty in the observations is much higher for the material collected with the high frequency sonar (Simard SA 950) in 1992 (Table 3). The frequency of undetermined schools may affect the frequency of disturbed schools, as it is not known if undetermined schools were influenced by the vessel or not. There were mainly two reasons for difficulties in judging swimming pattern of certain schools. First, short observation time of the schools combined with rather irregular swimming patterns made it difficult to see any consistent swimming trace of the respective schools. This was the main reason for the high frequency of undetermined schools (\approx 19%, Table 3) in data from the North Sea cruise in 1992. The shorter detection range of the sonar, combined with a rather narrow sonar sector (45°) led to short observation time of many of the schools. Secondly, schools may show very irregular swimming behaviour, not obviously following any consistent course. Such schools were categorized as undetermined as it is not known whether this behaviour was due to some kind of avoidance swimming in the vicinity of the vessel or that those schools were undisturbed and just swimming around within a narrow area. No difficulties were met in the judging of the swimming pattern of the capelin schools.

The overall low reaction frequency of capelin (Table 3) indicates that this species is relatively insensitive to stimuli from a cruising vessel compared to other pelagic species, e.g. herring, even under circumstances of good sound propagation as in the Barents Sea during winter. This low degree of avoidance is in accordance with earlier observations on this species (Olsen, 1971; Halldórsson and Reynisson, 1982; Olsen *et al.*, 1983, Olsen, 1990).

Swimming patterns of herring schools indicated that 60-70% of the schools that reacted, actually moved towards the sailing path of the vessel. This herding effect is assumed to happen because of the lobes of sound intensity out from each side of the vessel (Urlick, 1983). A similar swimming pattern has also been observed for the North Sea herring (Misund and Aglen, 1992).

Migration directions and migration speed

Means of average swimming directions in the North Sea in 1991 showed that the schools were generally swimming in southerly directions, and the herring survey in 1992 gave similar results (Figs. 3 and 4). North Sea herring surveys were in both years conducted in July. The observed similarity in swimming directions is an interesting observation, and the fact that this seems to be consistent between years may give reason to speculate about possible dynamics in the migration pattern of herring in the North Sea. Earlier observations, mainly based on tagging/recapture studies, have shown that the mature components of the North Sea autumn spawning stocks (the Buchan and the Dogger bank spawners) have a similar anti-clockwise migration pattern around the middle and the northern North Sea. After overwintering in the Norwegian trench and Skagerrak, the herring feed during early summer on the grounds of the northern North Sea. In late summer, the herring migrate towards the spawning grounds off the northeast coast of Scotland and on the Dogger bank (Harden Jones, 1968). The spring spawning herring from the Skagerrak - Kattegat - Baltic Sea area extend their feeding migration during early summer northwards over the Norwegian trench to 61-62°N. In July-August this herring start to migrate south towards overwintering grounds (Bakken *et al.*, 1991). The migration routes of these herring stocks show a general tendency to spread towards north during their feeding migration. When the intensity of feeding activity levels off and spawning approaches, the North Sea stocks withdraw southwards into the North Sea again. At the same time the spring spawning herring begin their return migration for overwintering. In late July, the autumn spawning herring might be on their migration towards the spawning grounds off the east coast of Britain, at the same time as the spring spawning herring will be withdrawing to their overwintering grounds in Skagerrak, Kattegat, and the western parts of the Baltic Sea.

The average migration speed of about 0.2 m s⁻¹ of the herring schools in 1991 gives a net movement of the population of about 9 nautical miles per day or 270 nautical miles per month. This speed is quite plausible for the summer migrations of the North Sea herring population. The average migration speed of the herring schools recorded during the mini-survey in 1992 was about 2.5 times faster. Such rapid migration may probably occur when adult herring are moving through a "transportation distance". The capelin migration was very slow, indicating little movement in the population at that time of the year. Probably, the spawning migration of the maturing capelin to the Norwegian coast was just about to start.

During the mini-survey, about twice as many schools were observed during the first traversal than the second. The reason for this great difference is believed to be migration of the herring. During the time elapsed between the first and second covering, most of the fish migrated southwards out of the survey area. In order to 'catch up' with the population for the second

measurement, the survey grid lines should be moved more towards south and southwest. Sonar data from the first traversal would probably have proven excellent for the estimation of the distance migrated by the stock during the short (but crucial) period between the two measurements. This can be regarded as an example showing how unstable aggregations of fish can be in areas of high migration activity, giving sudden variations in fish abundance from one time to another. Sonar observations made during surveys can be of value for prediction of such changes.

Swimming speed

The mean swimming speed of the herring schools varied of about 1.2 m s^{-1} , which is within the range of laboratory measurements and theoretical considerations (He and Wardle, 1988; He, 1993), as well as values observed during sonar surveys on herring in the North Sea (Aglen, 1985; Misund, 1990; Misund and Aglen, 1992). Figure 4 indicates clearly that some random error is apparent in the sonar registrations. High values seem to occur independently of the length of the observation time (number of pings), which indicate that these are not caused by any systematic errors. It is concluded that the 'jumps' in sonar estimates are random. The sonar errors operate in both directions, i.e. they can lead to overestimating ping values as well as underestimating values. During each school observation much too high values can be registered, but too low values must also occur. However, the range of underestimated values is truncated because the values can never be lower than zero. This might lead to an upward bias in the swimming speed estimates. In spite of this, the mean values of swimming speeds seem to give plausible results. This is at least apparent regarding the herring as the swimming capacity of that species is rather well known.

The observed speed values of capelin schools (mean: 0.82) are somewhat high compared to those of Miller and McNerney (1978), who recorded average swimming speed of a capelin school (length $18 \pm 1 \text{ cm}$) kept in captivity at 3.5° - 5.6°C to be 0.35 m/sec . The observed mean length of the capelin during the Barents Sea cruise in January 1992 was 13.4 cm , and the capelin schools were observed at sea temperatures around 3°C . If the maximum sustained swimming speed (U_{ms}) of a pelagic species of 13.4 cm is calculated according to He (1993), the result is 0.86 m s^{-1} , which is in agreement with the total results of non-reacting schools in Table 5.

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Table 1. *Cruises during which material was collected for this study.*

Cruise	Vessel	Area	Period	Species	Sonar type
1	Johan Hjort ^a	North Sea	6. - 23. July 1991	Herring	Simrad SR 240
2	G. O. Sars ^b	North Sea	25. - 27. July 1992	Herring	Simrad SA 950
3	Johan Hjort	Barents Sea	18. - 30. January 1992	Capelin	Simrad SR 240

^a 64, 4 m., 1950 grt.^b 70 m., 1447 grt.**Table 2.** *Numbers of schools where behaviour parameters were sampled from sonar to external loading device during normal cruising of research vessel. Mean, minimum and maximum time of observation (sec) are given for each survey.*

	Numbers of schools	Observation interval (sec)		
		Mean	Min	Max
Johan Hjort, July 1991	114	73	7	180
G. O. Sars, July 1992	86	46	10	124
Johan Hjort, January 1992	33	75	17	208

Table 3. *Numbers and relative frequency of schools grouped in each of the classifications, on the basis of observed swimming pattern.*

Cruise:	Category of swimming pattern						Total number
	Migrating		Avoiding		Undetermined		
	Numbers	%	Numbers	%	Numbers	%	
North Sea 1991	85	77.3	21	19.1	4	3.6	110
North Sea 1992 ^a	43	57.3	18	24.0	14	18.7	75
Barents Sea 1992	29	93.5	2	6.5	None		31

^aSecond traversal of minisurvey included

Table 4. *Swimming speeds ($m s^{-1}$) as estimated by sonar of all herring schools in the North Sea 1991, classified according to swimming pattern categories.*

Area	Categories	Numbers	Mean	Min	Max	SD
North Sea 1991	Migrating	85	1.22	0.49	2.44	0.42
	Avoiding	21	1.18	0.45	1.95	0.44
North Sea 1992	Migrating	38	1.17	0.56	2.57	0.47
	Avoiding	11	1.33	0.67	2.40	0.58
Barents Sea 1992	Migrating	29	0.82	0.40	1.44	
	Avoiding	2	0.69	0.50	0.88	

Table 5. *Summary of the results of the migration pattern analysis showing mean values of different migration parameters.*

Migration parameters:	Cruise and target species		
	North Sea 1991 85 herring schools	North Sea 1992 43 herring schools	Barents Sea 1992 29 capelin schools
Migration speed ($m s^{-1}$)	0.19	0.52	0.11
Migration direction (deg)	194°	196°	2°

Figure texts:

Figure 3. *Survey grid map showing observed migration pattern during echo survey in the North Sea 6. - 23. July 1991. Arrows on survey grid lines indicate location and calculated mean swimming course of each school that showed no reaction to the vessel.*

Figure 4. *Survey grid lines and observed migration pattern of the herring schools recorded during the survey 25 - 27 July 1992. Stipled lines show depth contours in meters. Southern area covered twice is marked within box. Stipled lined arrows show migration directions of schools observed during the second traversal.*

Figure 5. *Survey grid map showing observed migration pattern of capelin during echo survey in the Barents Sea 18-30 January 1992.*

Figure 1. A: *Plot of observed swimming speed ($m s^{-1}$) with increasing numbers of recorded pings tranceived by the sonar for all herring schools respectively included in the data set collected with the Simrad SR240 sonar in the North Sea in 1991. B:* *Mean values per ping with standard error limits calculated from the material in Figure 4A.*

Figure 2. *True motion examples of horizontal movements of herring schools in relation to survey vessel, observed in the North Sea in July 1991. One school of each reaction pattern category is shown. A: No reaction. B: Reacted to vessel. C: Unable to classify (See next page). Real length of vessel 64.5 m.*

Figure 2 (continued). *See Figure text on previous page.*

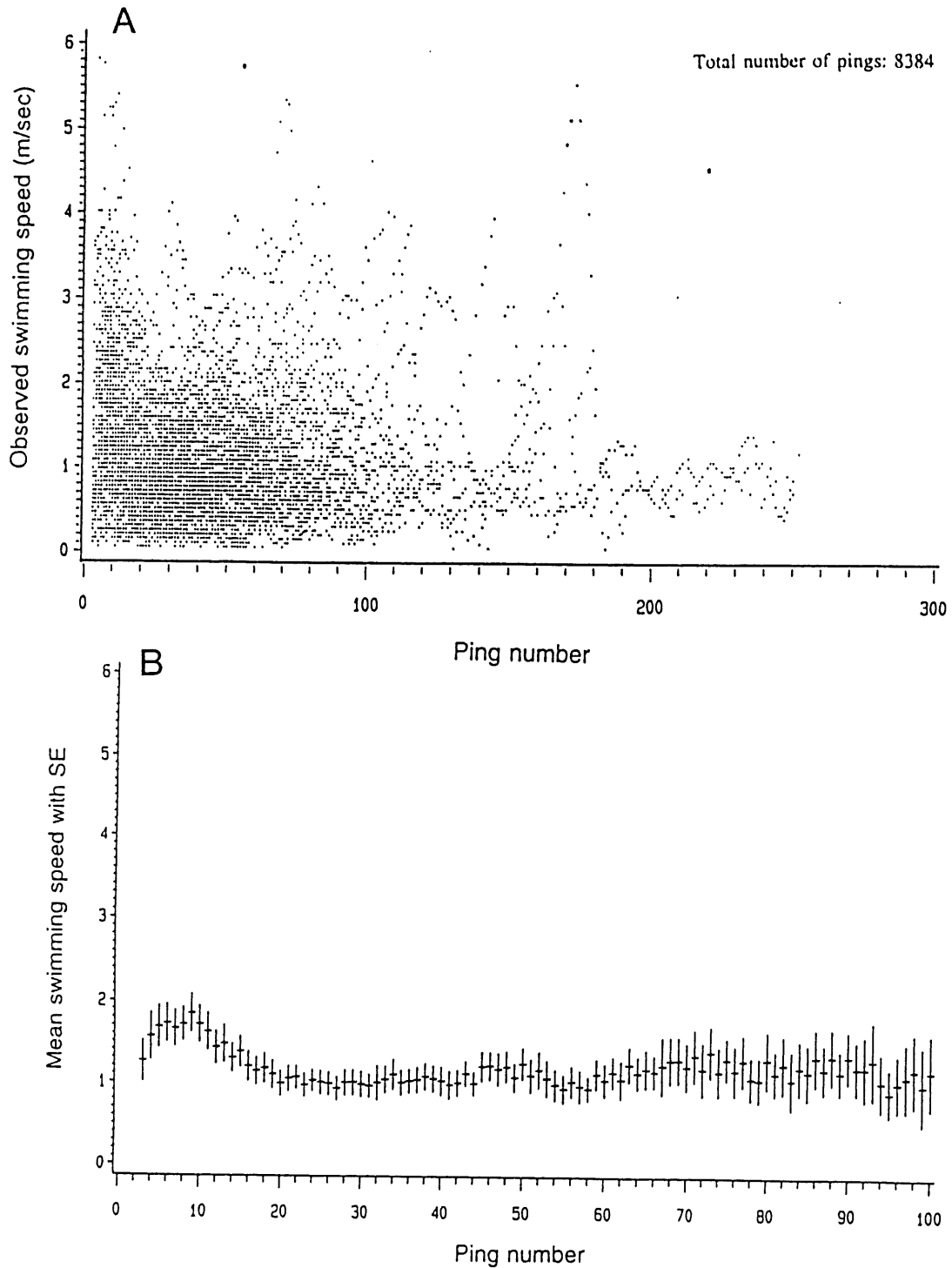


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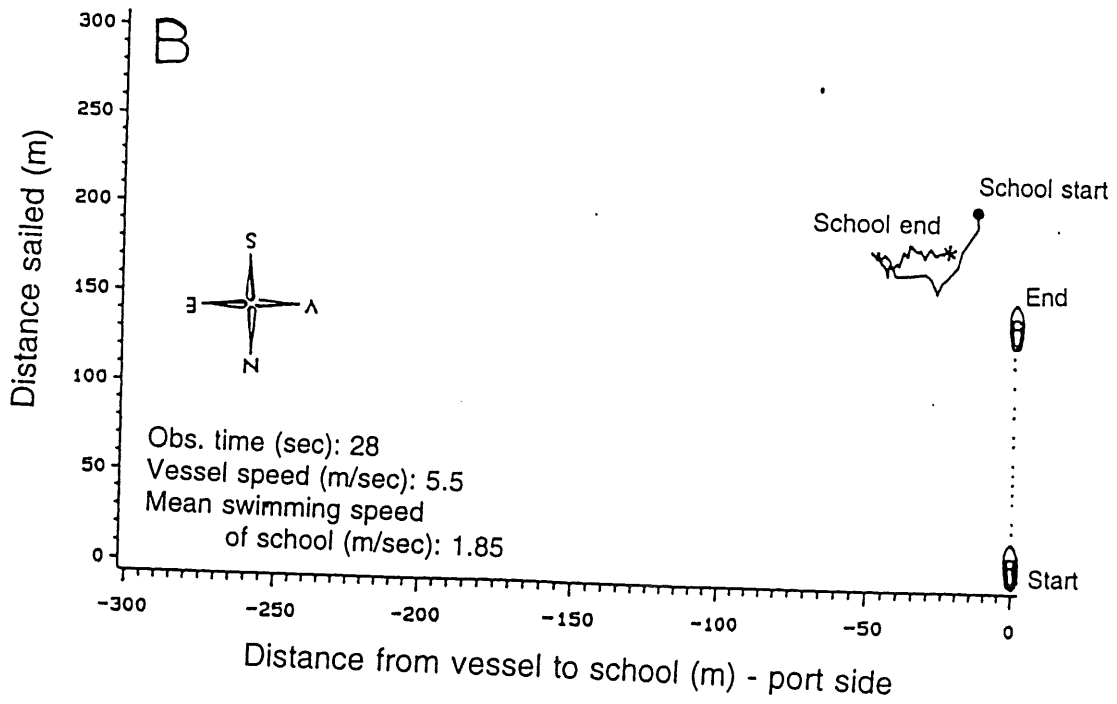
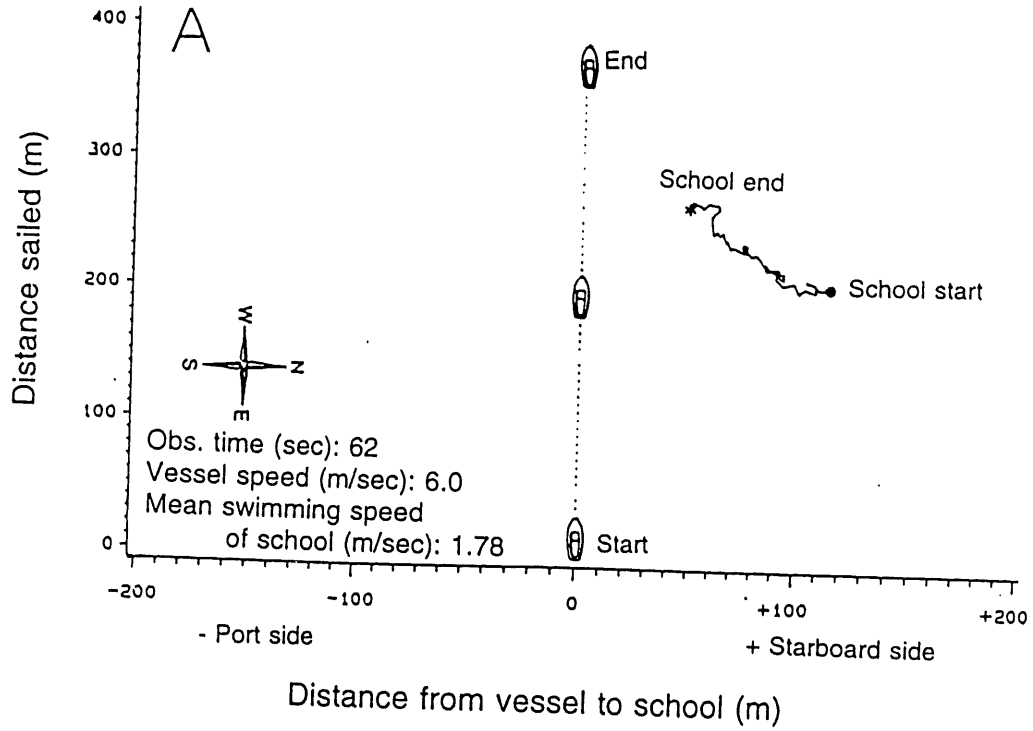


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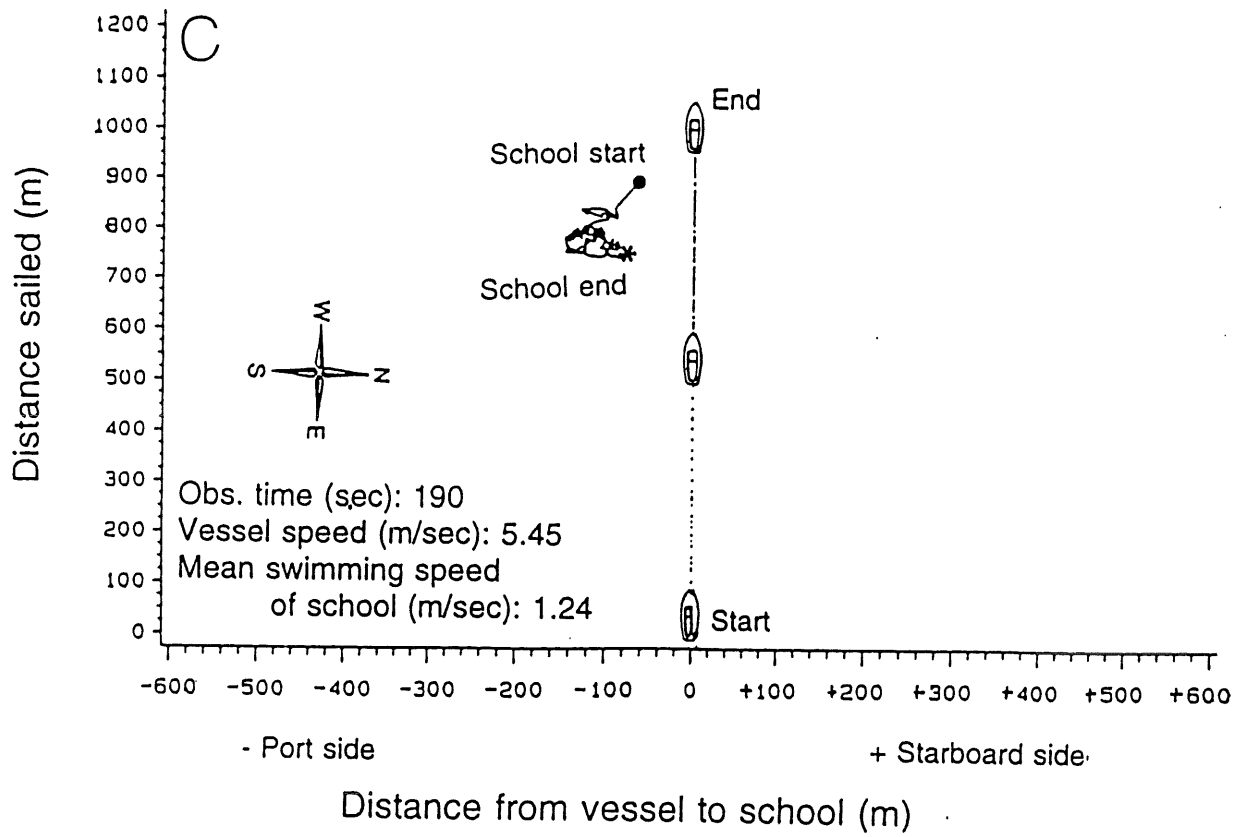


Figure 2 (continued). See Figure text on previous page.

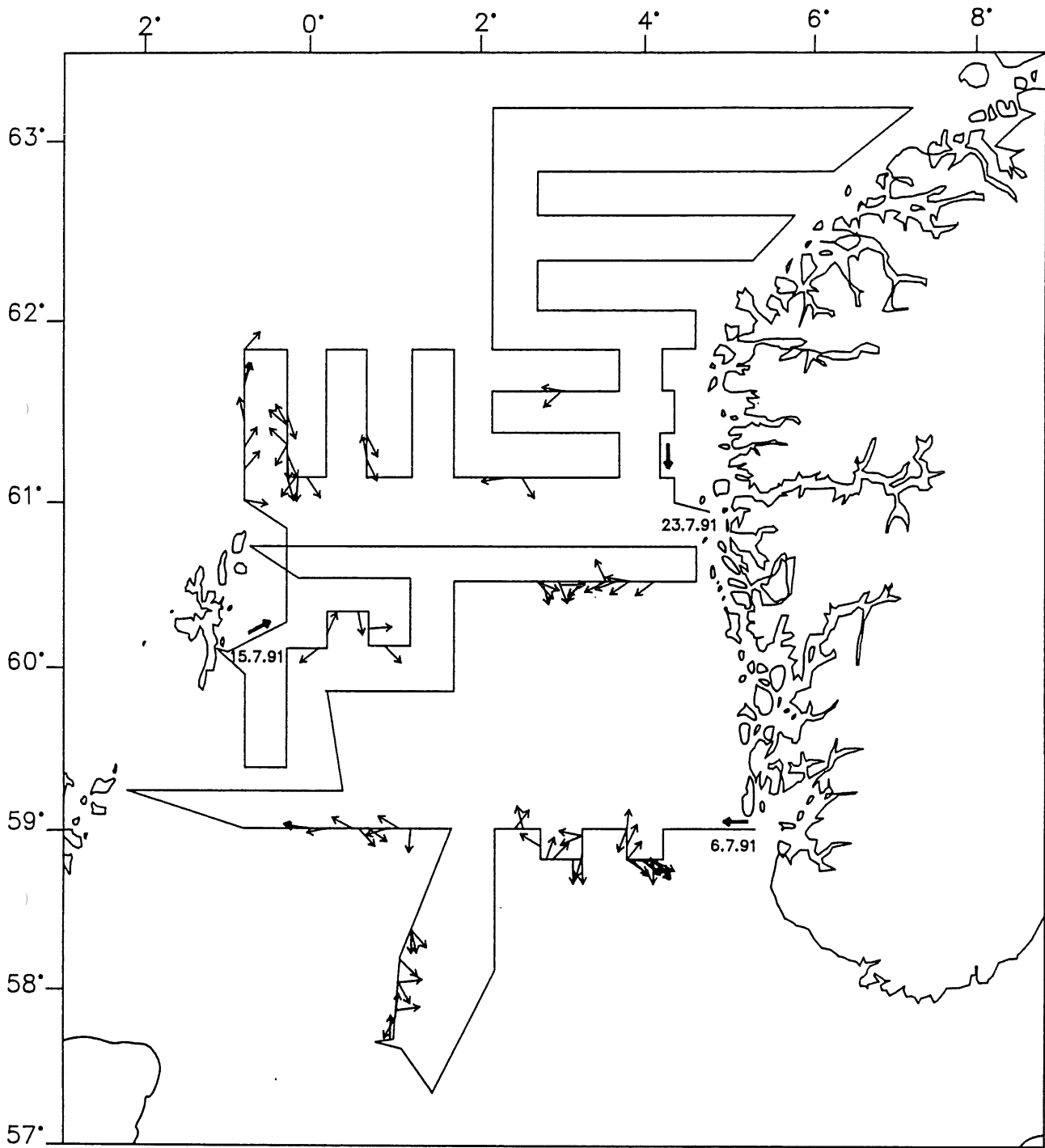


Figure 3. Survey grid map showing observed migration pattern during echo survey in the North Sea 6. - 23. July 1991. Arrows on survey grid lines indicate location and calculated mean swimming course of each school that showed no reaction to the vessel.

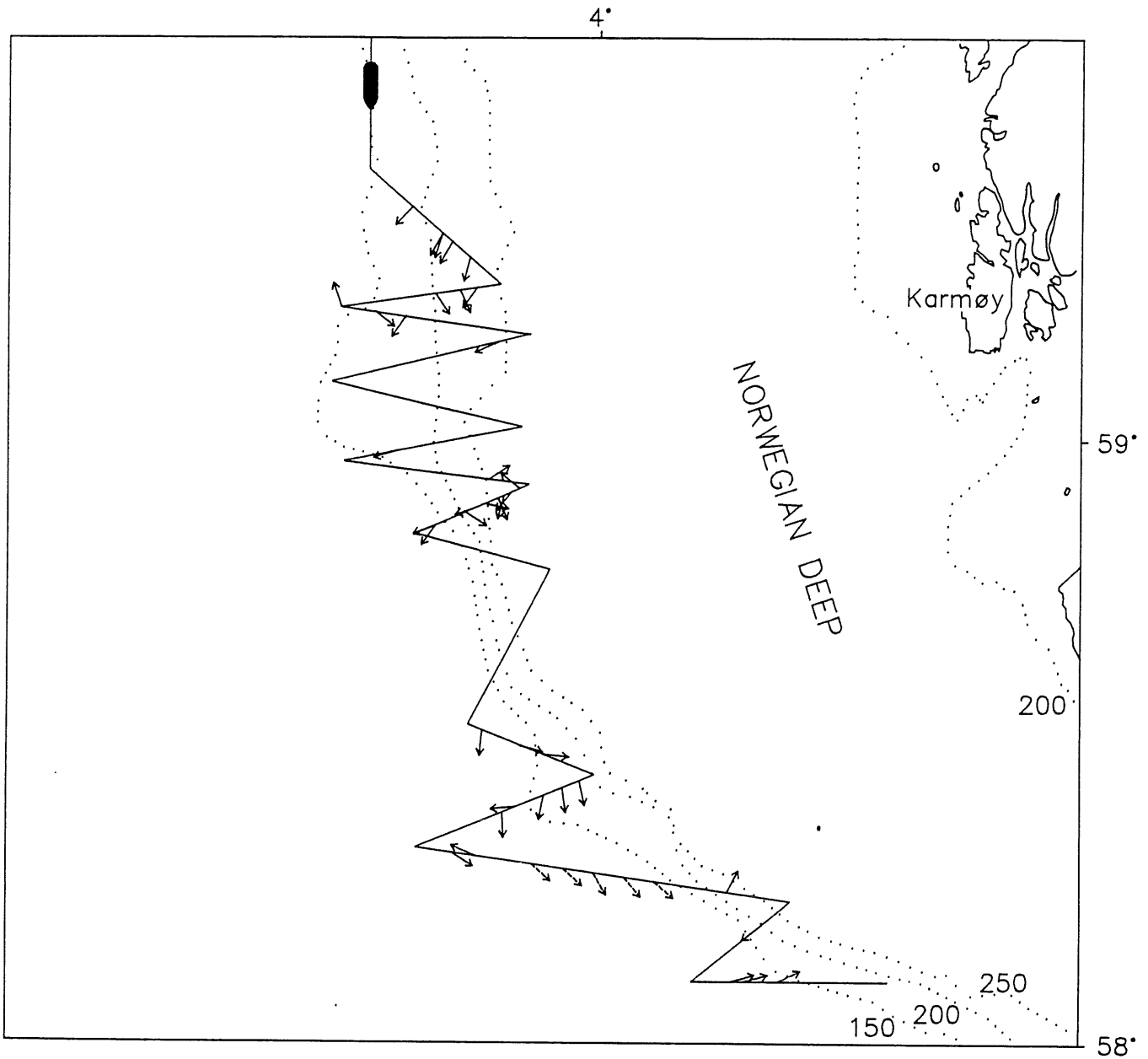


Figure 4. Survey grid lines and observed migration pattern of the herring schools recorded during the survey 25 - 27 July 1992. Stippled lines show depth contours in meters. Southern area covered twice is marked within box. Stippled lined arrows show migration directions of schools observed during the second traversal.

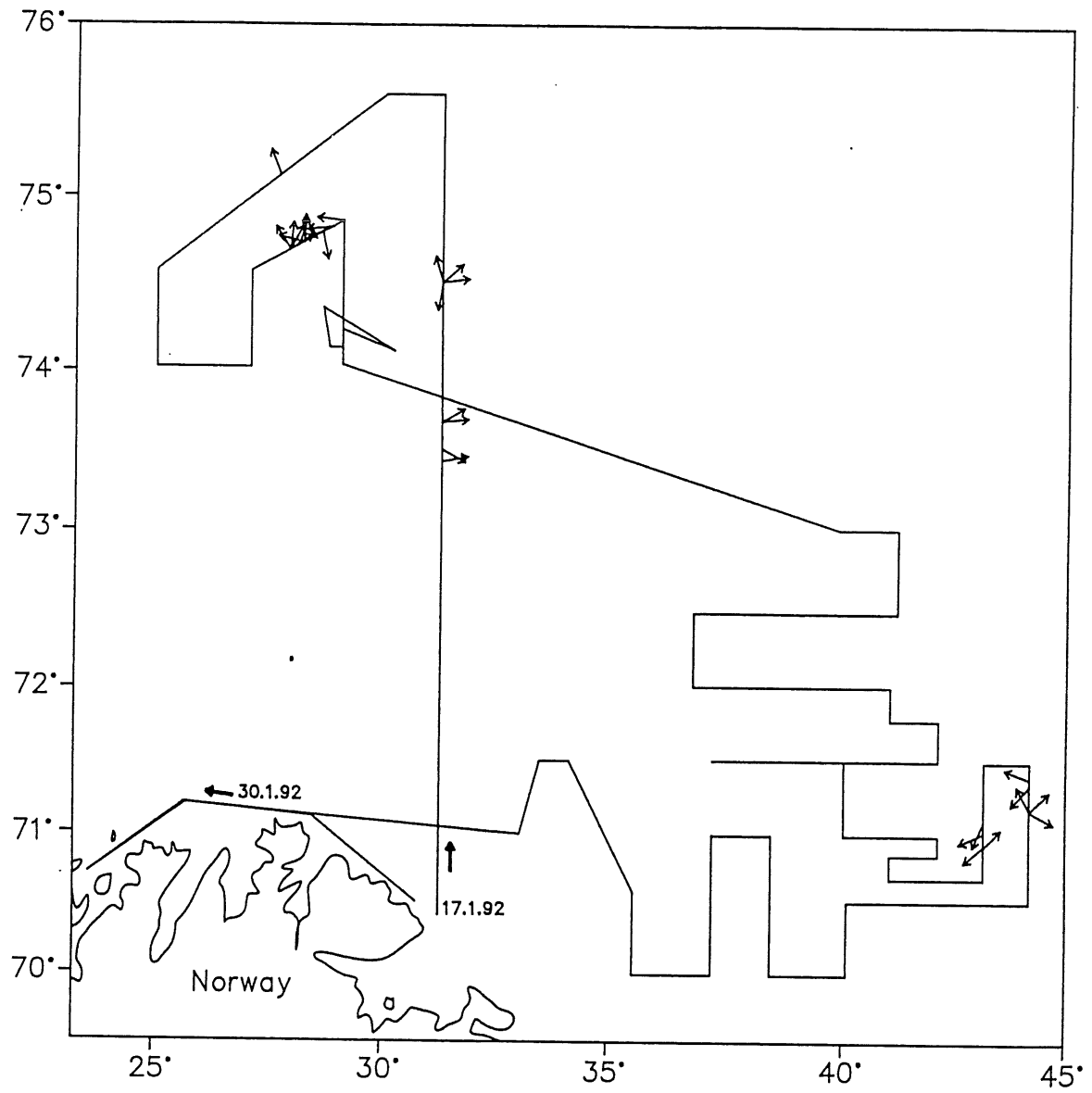


Figure 5. Survey grid map showing observed migration pattern of capelin during echo survey in the Barents Sea 18-30 January 1992.