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ACOUSTIC TELEMETRY: PROGRESS AND POTENTIAL IN UNDERSTANDING FISH BEHAVIOUR

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INTRODUCTION

Patterns of behaviour can determine the distribution of fish populations and systematically bias the results of surveys used to estimate fish abundance[1]. Seasonal changes in geographical distribution affect availability, and vertical migration may make fish inaccessible to bottom trawls by night. Vulnerability to fishing gear undoubtedly varies with environmental factors, such as light intensity and water clarity, and possibly also with changes in the physiology of the fish.

At Lowestoft some advances have been made over the last twenty years in describing and understanding various aspects of marine fish behaviour relevant to these problems. Progress has largely been a result of the application of acoustic telemetry, which has allowed us to follow the movements of unrestricted, identified fish in the open sea for several days at a time. Observations of the behaviour of individual tagged fish have been used to predict patterns of behaviour in natural populations, which have then been tested by independent methods[2].

We will attempt in this paper to outline briefly some of the advances that have been made at Lowestoft and the potential that we see to develop the programme in the future.

PROGRESS

The acoustic tracking system developed at Lowestoft is based on the high- resolution sector-scanning sonar invented by Dr G. M. Voglis of the Admiralty Research Laboratory (ARL) at Teddington[3], and a small transponding acoustic tag developed by the Lowestoft laboratory's own electronic engineers[4]. The technique has been used: (i) to follow the movements of migratory fish in the southern North Sea; and (ii) to describe the reactions of plaice to a Granton otter trawl and measure the efficiency of the gear. A larger and more complicated acoustic tag has been used to determine the compass- heading of free-ranging fish and telemeter this information back to the tracking vessel. The gear work has been described in earlier papers[5,6]; here we will concentrate on the migration story and the results obtained with the compass tag.

High-resolution sector-scanning sonar

The sonar, which operates at a frequency of 300 kHz, scans a 30° beam out to ranges of 360 m, with bearing and nominal range resolutions of 0.33° and 8 cm, respectively. It is installed in a package which corrects for the motion of the ship and allows the transducer to be used in both horizontal and vertical modes[7]. The corresponding pictures are presented on a B-scan display and the high-resolution of the system gives a very detailed picture of bottom topography, wrecks and fishing gear. The facility for horizontal and vertical scanning allows the position of a target to be determined very quickly in all three dimensions and the ability to determine depth has proved to be particularly important. The original ARL equipment was replaced in 1974 by a solid-state system developed at Lowestoft[8]. The MAFF scanner with improved controls, digital signal processing, new displays and computer data-logging facilities was transferred to our new research vessel RV "Corystes" when she replaced RV "Clione" in 1988.

A transponding acoustic tag

The original transponding acoustic tag was developed in 1971 in order to label individual fish with a strong and unambiguous signal, which could be detected against the echo from the sea bed. The tag is small (5 cm long x 1 cm diameter) and unlikely to affect the swimming performance of the fish in any significant way[9]. It is attached to a plaice by a fine nylon cord, which is tied to the eye of a Petersen tag. On a cod it is attached to a pair of spaghetti tags and mounted just below the dorsal fin. Plaice can be released directly from the ship, but cod (which have a gas-filled swimbladder) need to be held in a cage first, if they are to be released on the sea bed in a state of neutral, or near-neutral, buoyancy[2].

Sector-scanning sonar and transponding acoustic tags have been used since 1971 to follow the movements of plaice, sole, cod, dogfish, eels and salmon in the North Sea. We have learned a lot about fish behaviour as a result of this tracking work but in the limited space available to us in this paper we will concentrate on the plaice (Pleuronectes platessa L.).

Detailed studies in the southern North Sea have shown that in the plaice there are two patterns of vertical migration (Figure 1), which produce movement on two distinct geographical scales. On their feeding grounds in summer, and again on their spawning grounds in winter, plaice remain on the bottom by day and move into midwater at night[10,11]. The vertical migration has a diurnal (approximately 24 h) periodicity[12] and the vertical movements are usually out of phase with the tide. The fish is carried in whichever way the tidal stream is flowing when it leaves the bottom and as a result does not progress in a consistent direction. Its movements can be shown theoretically to be contained within a limited geographical area that is smaller in extent than a typical spawning or feeding ground[11].

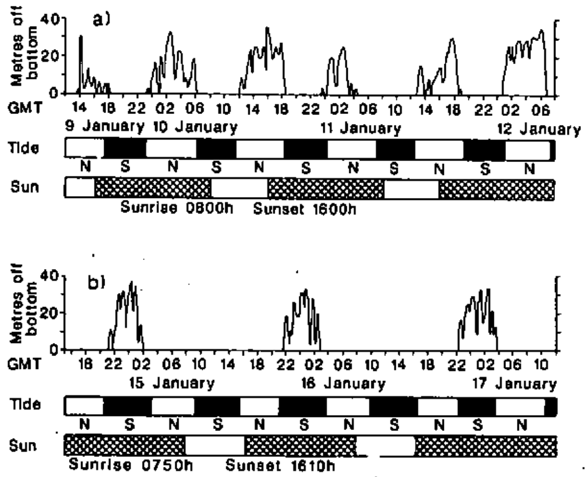

Figure 1
Patterns of vertical migration in the plaice: (a) the semi-diurnal pattern of vertical migration in a fish moving north by selective tidal stream transport; (b) the diurnal pattern of vertical migration, which in this particular instance is also initially in synchrony with the south-going tidal stream. Both fish were tracked on a spawning ground in the Southern Bight of the North Sea in January. (M. Greer Walker, unpublished observations.)

Migrating plaice, which in the southern North Sea travel distances of 200-300 km before and after spawning each year, exhibit a different pattern of behaviour which we have called selective tidal stream transport[13]. The fish move in a consistent direction, and can cover 20 km or more in 24 h. The vertical movements occur in phase with the tides and have a semi-diurnal (approximately 12 h) periodicity. The fish leave the bottom at one slackwater (Figure 1a) and are carried downstream for the duration of the transporting tide. They return to the bottom at the next slackwater and maintain station for the duration of the opposing tide (Figure 2). In the autumn, maturing plaice migrate into the Southern Bight of the North Sea on the south-going tide. Spent plaice migrate out of the Southern Bight in the spring on the north-going tide[14].

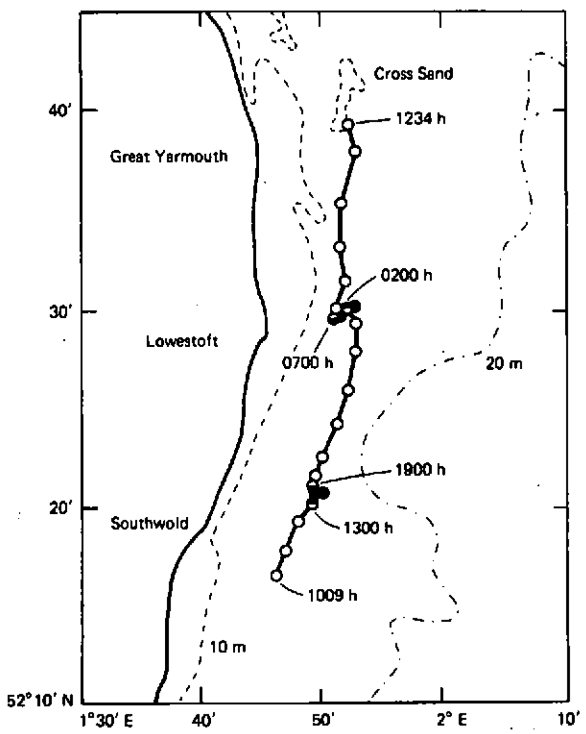

Figure 2
Track chart of plaice 7 released on 12 December 1971, indicating the position of the fish at hourly intervals. Open circles correspond to a north-going tidal stream, closed circles to a south-going stream; half-closed circles indicate times of slackwater[10].

A telemetry compass tag

The transponding acoustic compass tag, which was also developed at Lowestoft[15, 16], is considerably larger (7 cm long x 2.1 cm diameter) than the original transponder. It has, however, been successfully deployed on seven plaice and three salmon to produce a continuous record of the position, depth and heading of the fish in real time for periods of up to 70 h. The compass tag is attached to a plaice by two conventional Petersen disc tags and is carefully aligned along the axis of the body on the upper (right-hand) surface. The compass reference is provided by a magnet attached to a slotted disc, which is mounted on a jewelled pivot. The bearing of the slot is detected optically by a circular array of eight infra-red emitters and detectors and the heading of the fish can thus be assigned to one of eight nominally 45° compass sectors. When the tag is interrogated at 300 kHz, it responds with a reference pulse, which is used to determine the position and depth of the fish in the usual way[13]. The heading of the fish is indicated by a second pulse and the delay between the two signals (ranging from 24 to 66 ms in seven 6 ms steps) identifies the relevant sector. The two pulses can be displayed on a paper recorder as well as on the sonar screen.

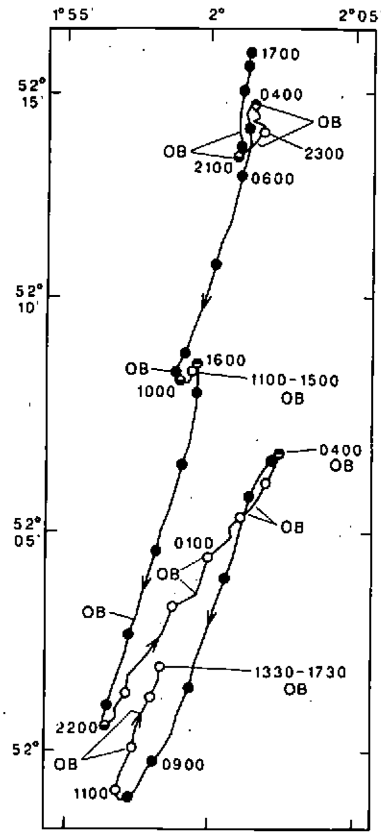

Figure 3
Track of plaice 4 fitted with a transponding acoustic compass tag and released at 1700 h 26 May 1980. Hourly positions are indicated and the conventions are the same as in Figure 2.

Five compass-tagged plaice were tracked off East Anglia in 1979 and 1980 for periods of up to 55 h. The compass heading of each fish was recorded on paper at 1 s intervals and subsequently subsampled at 20 s intervals. The tracking was carried out in the summer and the fish showed three different patterns of behaviour. One fish (compass tag 5) exhibited tidal stream transport and moved a net distance of 62 km to the north over the course of 4 transporting tides. Two plaice (CT 2 and 3) showed a consistent pattern of diurnal vertical migration. The other two fish (CT 1 and 4) changed from one pattern of vertical migration to the other during the track (Figure 3). Although the analysis of the plaice compass tag data is not yet complete, three general conclusions can be drawn.

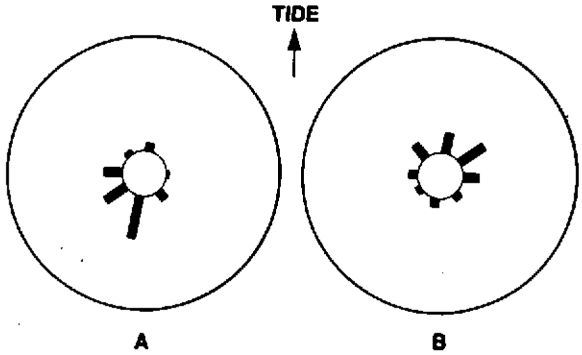

Figure 4
The heading, relative to the tide, of 5 adult plaice as indicated by compass tag with data sampled every 20 s.
A: On the sea bed; from observations over a total of 92.6 h comprising 12 periods of at least 1.8 h each.
B: In midwater (3 m or more from the sea bed); from observations over a total of 43.4 h comprising 17 periods of at least 1 h.

Plaice on the bottom head into the tide (Figure 4a) and reverse their heading in response to a reversal in the direction of the current. The change of heading occurs during the accelerating phase of the tide, within 1-2 hours after slack-water[2] and this lag accounts for some of the downtide headings shown in Figure 4a.

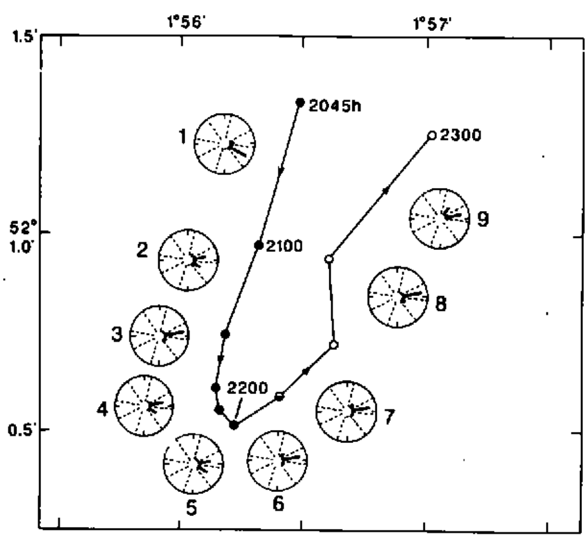

Figure 5
The compass heading of plaice 4 in midwater between 2045 and 2300 h 27 May 1980 for each of nine consecutive 15 min periods. The compass heading was sampled at 20 s intervals and each circular distribution is therefore based on a total of 45 samples.

Plaice in midwater can maintain a consistent heading, remaining within two 45° compass sectors for an hour or more. This behaviour can occur on dark nights, when neither the moon nor the stars are visible, and when the fish is probably too far away from the bottom to detect the current through the normal visual or tactile clues[6,17]. The fish may head in one direction while being carried over the ground by the tide in another (Figure 5) and its swimming speed is often sufficient to be reflected in the resultant ground track. Fish heading up or downtide move along the tidal stream axis; fish heading across the tide depart from it. This latter behaviour occurred most noticeably during the track of fish 2. The track of this fish has already been described in detail[17].

The orientation of compass-tagged plaice in midwater is not random. There are occasions when the fish head in the opposite direction to the current and extended periods during which they head across the axis of the tidal stream, as described in the previous paragraph. On average, though, they head downstream (Figure 4b). This conclusion is supported by a complementary analysis, in which the average heading of 12 individual plaice was derived from the ground track of the fish and the predicted tidal stream excursion for each of 34 extended midwater excursions[18]. These fish exhibited tidal stream transport and on average travelled further than tidal stream during the transporting tide (Figure 6a). They swam at a moderate speed (mean 0.6 body lengths s^{-1}) and mostly headed downtide (Figure 6b). Four of the excursions were derived from the track of a compass-tagged fish (CT 5); the other 11 fish were tagged with a standard transponder.

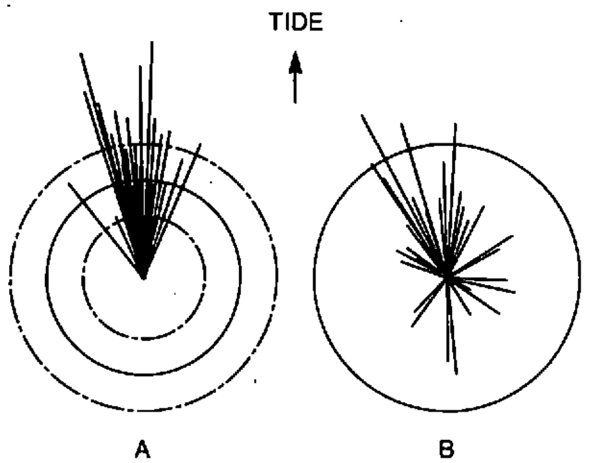

Figure 6
(a) The net movements of 12 plaice over the ground during 34 midwater excursions (minimum duration 100 min) normalised in distance and direction to the tidal stream. The circle represents the predicted distance travelled by the tidal stream and the broken circles the equivalent 95% confidence limits; (b) the speed and direction of plaice through the water for each of the 34 midwater excursions depicted in Figure 6(a) normalised to the direction of the tidal stream. The circle represents a speed of 1 body length s^{-1}.

POTENTIAL

The patterns of behaviour we have described in the plaice suggest that the tidal streams, which are a dominant feature of the circulation on the European continental shelf, are a major factor in the distribution of demersal fish populations. But there are still many unresolved questions and the answers are fundamental to our long-term understanding of fish migration, the temporal and spatial distributions of fish populations, and the environmental factors, such as climatic change and pollution, which may alter or disrupt them.

The discovery of selective tidal stream transport has allowed us to make some progress with the production of a simple model to explain the distribution of fish stocks in hydrodynamic terms[11]. This could be useful not only in terms of stock management, but also in relation to understanding the spread of disease and the impact of pollution on fish. But, before the model can be applied with confidence to the solution of practical problems, we need to know a lot more about the behaviour of the fish and in particular their mechanisms of migration. Do all populations of plaice on the European shelf migrate by selective tidal stream transport or is this behaviour restricted to areas of fast and directional tidal streams, such as the Southern Bight and English Channel? What physiological factors determine the switch from one pattern of vertical migration to the other? How does the fish select the appropriate transporting tide, bearing in mind that it moves in opposite directions before and after spawning? Similar behaviour occurs in sole[19] and cod: is it a general phenomenon or does it occur only in demersal species? What is the principal role of selective tidal stream transport? Does it conserve energy, which can then be used for reproduction? Does it, alternatively, determine the destination of the migrating fish, which may have no ability to navigate and thus no way of determining the relative locations of its spawning and feeding grounds?

Some of these questions are amenable to experimental investigation in the laboratory; others require observation or experiment at sea. Acoustic telemetry has the great merit that the movements of identified individual fish can be followed in the open sea independently of the constraints imposed by tanks or cages. But our present system is not appropriate for following fish for the long distances or periods associated with seasonal changes in distribution and it suffers from the great handicap that only one fish can be followed at a time.

The incorporation into telemetry tags of miniature sensors, which could, for example, measure temperature, salinity, light intensity and swimming speed, would enable us to test various hypotheses about the behaviour of fish in relation to environmental factors[20]. But such work is slow and major advances are only going to be made at a worthwhile pace if we can conduct long-term field experiments with large numbers of fish simultaneously. To do this we need new techniques and here we are considering using data storage tags, sonabuoys and ultimately pop-up tags, which can be released from the fish at a predetermined time, float to the surface and telemeter data back to the laboratory by satellite. Our first objective is to develop a tag capable of recording and storing information on the depth of the fish for many months on end and of being recovered through the commercial fishery. We plan to use it to address some of the outstanding questions about selective tidal stream transport that we cannot address in the tidal stream tank that we have built in the laboratory.

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