ACOUSTIC TRACKING OF FISH IN THE SEA: CURRENT STATUS AND FUTURE PROSPECTS

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1. INTRODUCTION

For the rational management of fisheries, fundamental knowledge of the distribution and migratory behaviour of commercially important species is of vital importance. Information on the migration and distribution of fish has been recorded historically, largely derived from knowledge of where and when fish were captured by the commercial fishing fleet, but our ability to locate and estimate the abundance of fish stocks has also improved with coordinated international programmes of fish stock assessment. Routine monitoring of commercial catches is now well established, and surveys of fish egg and larval abundance and distribution, coupled with acoustic survey techniques are employed to quantify exploitable fish stocks.

More intimate knowledge of fish movements in the sea on a daily basis is not widely available. Extensive studies of the ecology of tropical reef species have been conducted by diving observations eg Sale [1] and observations of the reactions of fish to fishing gears in temperate waters by divers and television have been described by Wardle [2]. The use of underwater television for fish behaviour observations has also been recently reviewed by Wardle & Hall [3] and they draw attention to the limitations of television for observing the natural behaviour of fish in deeper waters with low natural light intensity.

Biotelemetry techniques using acoustic tags in fresh water lakes were first described by Johnson [4]. The use of acoustic tags was reviewed by Stasko & Pincock [5] and Mitson [6] and methods of tracking fish at sea have been reviewed by Hawkins & Urquhart [7] and more recently by Priede [8].

The principal methods of acoustic tracking are divided into active methods, where active sonar is employed, and passive methods using hydrophones and receivers to detect signals from acoustic transmitters carried by individual fish. In this review some examples of acoustic tracking methods are described as illustrations of the principles and limitations of the techniques. The main purpose of the paper, however, is to review acoustic methods of determining fish movements which are currently in use and to speculate on future requirements from a biological perspective.

2. PRESENT ACOUSTIC TRACKING METHODS

2.1 Active Sonar

The main advantage of using active sonar is the ability to study fish in the wild with minimum disturbance to their natural activities. Echo sounders and sonars are widely used for fish detection and it is sometimes possible to use or adapt them for fish behaviour studies. There are, however, a number of limitations which in general makes active sonar more suitable for schools of fish than for individuals.

ACOUSTIC TRACKING OF FISH IN THE SEA: CURRENT STATUS AND FUTURE PROSPECTS

Individual fish are poor and highly variable acoustic targets although those with swimbladders are better reflectors of acoustic energy than those without. Typical fish shape results in the target strength being highly dependent on the angle of the incident acoustic wave. In addition, echo sounders and sonars need to be fairly sophisticated and linked into navigational systems in order to locate fish and track them successfully at sea. Sonars which are capable of resolving individual fish must operate at high frequency which results in greater attenuation and shorter range. The ship carrying the sonar must therefore manoeuvre closer to the fish with a greater danger of disturbance or simply make transient observations and measurements as the fish pass beneath.

2.1.1 Echo Sounders. Echo sounders are normally mounted on the hull of a ship and are used mainly as depth measuring devices for safe navigation. Other sounders are designed for the quantitative measurement of fish abundance by counting echoes from individual fish or integrating echo returns over a period of time. Echo sounders can also be mounted on fishing nets or in specially designed towed bodies. They can be useful for observing changes in vertical distribution and social behaviour at different times of the day and night or for studying the response of fish to fishing gears as described by Ona & Eger [9].

Two recent developments which expand the capability of vertical sounders are the dual-beam and split-beam types. Both were developed primarily for the direct measurement of fish target strength and the split-beam sounder has also found an application in the study of individual fish movements (Brede, *et al.*, [10]). The principles of the split-beam echo sounder are shown in Figure 1. It is, however, rarely possible to follow individual fish or even schools for extended periods using echo sounders.

2.1.2 Sonars. The simplest searchlight sonars operate in the same way as echo sounders but employ a trainable transducer so that the beam, which is normally narrower than an echo sounder beam, can be steered to point in any direction. This makes it possible to search around the ship in a way which is not possible with an echo sounder. More information can then be obtained about the horizontal and vertical distribution, movement and behaviour of fish schools. There are, however, great problems with this technique. Whether sweeping manually or automatically it takes some time to search the whole swept volume of water and if a target is located, considerable skill is required to keep the sonar trained. These problems are overcome to some extent by using more than one beam. A multi-beam sonar was used by Misund *et al.*, [11] to study fish swimming behaviour and vessel avoidance during acoustic surveys.

Electronic sector scanning sonar is another approach to rapid scanning. A relatively wide beam (about 30° x 30°) is transmitted to insonify a sector which is rapidly scanned by a very narrow (30° x 1°), electronically generated beam within the pulse duration. A raster display is produced showing all targets in the sector. The display is updated after each transmitted pulse. Fish targets can be more easily found and followed by moving the transducer around to keep the target centred on the raster display. A number of studies have taken place to examine fish activity using such sonars. They can be placed on the sea bed (Chapman *et al.*, [12] or mounted on a ship and used in conjunction with transponding acoustic tags attached to fish. These transponders are designed to receive transmissions from the sonar and send back a powerful pulse increasing the useful range. Mitson & Storeton-West [13] describe the technique, and a list of references relating to the application of the system appears in Arnold *et al.*, [14]. A deep-sea tracking system described by Armstrong *et al.*, [15] involves the use of transponding tags described by Bagley [16] and an active mechanically scanned sonar.

A development of the sector scanning sonar known as omni-sonar insonifies and scans a half-disc shaped sector approximately 20° x 180°. The complete half-disc can be rotated and tilted so that all of the hemisphere beneath the ship can be rapidly inspected. Schools can be automatically tracked and their movements displayed on a screen together with the ship's track derived from navigational instruments.

2.2 Passive Sonar

Passive sonar transmits no signal but detects signals generated elsewhere. Acoustic tagging together with passive sonar can give reliable, continuous, long-term information about the movements of individuals. Usually the animals are first captured, brought to the surface and often anaesthetised so that an acoustic transmitter can be attached, inserted or implanted before release. This limits the depth from which some species can be taken to about 20 m to avoid rupture of the gas-filled swimbladder. In addition, care has to be taken to minimise handling and time out of water. Large fish can, however, be induced to voluntarily ingest transmitters encapsulated in bait. This tagging technique has permitted the study of deep-sea fish at depths of 4,000 m with remote pop-vehicles carrying the receiving equipment (Priede & Smith, [17]) and could also be applied to the study of shallower water species avoiding any pressure change problems during the tagging process (Armstrong *et al.*, [18]).

2.2.1 Static Passive Tracking Systems. A fixed hydrophone array system (Fig. 2), which relies on the measurement of acoustic signal time delays and is used in conjunction with pulsed ultrasonic tags, has been described by Hawkins & Urquhart [7] and further developments reported by Urquhart & Smith [19]. Once established, the equipment requires minimum operator intervention and can produce a continuous series of position fixes about once per second with high precision. The system has been employed to investigate the movements of marine crustaceans and fish in inshore waters where cables can be laid to a monitoring station on land. During recent acoustic tracking studies in Scottish and Norwegian coastal waters individual tagged fish have been observed for periods of up to 28 days. Detailed daily patterns of movement for juvenile saithe, *Pollachius virens* L., have been reported (Glass *et al.*, [20]; Bjordal & Johnstone [21]). An example is shown in Figure 3. On occasions, several fish have been tracked together and data collected on spatial relationships of individual fish within a school (Smith *et al.*, [22]).

Another hydrophone array system for use in the sea using radio link telemetry has been developed using hydrophones connected to moored radio buoys (Fig. 4; Bjordal *et al.*, [23]). The hydrophones can transmit to each other to measure and update the relative positions of all the hydrophones in a group. The signals from tagged animals in the area are also picked up and used to calculate position. All data is transmitted by radio signals to a control vessel and the system has the advantage that hydrophones can be recovered and redeployed if tagged animals move and tracking is not confined to a fixed area.

A position fixing system requiring only two hydrophones and pingers synchronised with an external clock has been described by Holand & Mohus [24]. A sonar buoy system for use in estuaries (Solomon & Potter [25]; Fig. 5) has been used to detect acoustic signals from tagged fish and transmit radio pulses to a remote listening station onshore.

2.2.2 Mobile Passive Tracking Systems. The movements of fish, such as Atlantic salmon, *Salmo salar* L., which can undergo long distance oceanic migrations, may be studied by tagging individuals with ultrasonic transmitters. With their wider range of movements, however, a mobile tracking technique has to be adopted so that a vessel equipped with a directional receiver can maintain contact with the tagged fish (Fig. 6) and simultaneously obtain position data from navigational instruments. It is also necessary to measure or estimate the range and bearing from the tracking vessel to the signal source in order to calculate the absolute position of the fish. The technique is laborious, however, and individual adult salmon have been tracked for only limited periods at sea during the coastal migration phase of their return to spawn in fresh water (eg: Hawkins *et al.*, [26]). Other studies of salmon movements have investigated behaviour in estuaries where the range of movements for individual fish is more restricted (eg Stasko [27]; Potter *et al.*, [28]).

It is much more difficult to follow the movements of small fish because they can carry only a small transmitter. Most studies conducted with small fish have concentrated on salmonids but even so the detailed behaviour and movement patterns of juvenile salmon and sea trout (*S. trutta* L.) after migration to sea as smolts is largely unknown. External miniature acoustic transmitters have been used since the 1970s (Young *et al.*, [29]; Thorpe *et al.*, [30]) and similar devices are still being employed for attachment to salmon and sea trout smolts. The growth rate of salmon smolts fitted with such transmitters has been studied (Greenstreet & Morgan [31]) and they have been tracked as they emigrated from river to sea through the estuarine environment (Greenstreet, [32]). Miniature acoustic transmitters, developed by MAFF Fisheries Laboratory, Lowestoft, have been surgically implanted in salmon smolts during studies of movements in river and estuarine environments (Moore *et al.*, [33]; Moore *et al.*, [34]). Sea trout smolts, 200 to 230 mm in total length, (76 to 81 g weight) have also recently been tagged with external transmitters which weighed 1.5 g in sea water, (4.43 g in air) and briefly tracked in the sea (personal observation; Fig. 7).

3. ACOUSTIC TAGS

3.1 Tag Design

Nearly all ultrasonic transmitting tags employ short cylindrical transducers made from lead zirconate titanate (PZT) which are driven by a battery powered oscillator and coupled by a transformer. The ideal acoustic tag would be extremely small and light, have a high output, operate at low frequency to maximise its detectable range and have a battery life of a year or more. In practice these requirements conflict and the design of acoustic tags is always a compromise. For example, operating life and to some extent output power can be increased at the expense of a larger battery (increased size and weight) and smaller size can be achieved by using a smaller transducer and battery but with reduced output and operating life.

The choice of operating frequency is critical. Low frequency signals suffer less attenuation than higher frequencies. For maximum acoustic output tags must operate at a frequency which corresponds to the hoop mode resonant frequency of the transducer. A resonant transducer operating at a low frequency would appear to be the best choice. Unfortunately, mechanical resonance is related to physical dimensions and low resonant frequencies demand larger diameter transducers. For example a transducer resonant at 300 kHz measures approximately 6.0 mm diameter, a 75 kHz tag has a diameter of 12.5 mm and a 25 mm diameter transducer resonates at about 40 kHz. Tags which resonate at about 40 kHz or lower, although desirable for their greater range, can only be used with larger species of fish. Tags resonant at 300 kHz suffer much greater signal attenuation but they are useful because they can be made very small. Most tags operate at frequencies between 40 and 300 kHz.

Non-resonant tags are also widely used. Although output is less at an off-resonance frequency a small transducer can be selected to make miniature tags for special purposes. A tag for small fish for example might use a transducer of dimensions similar to a 300 kHz resonant transducer but operate at a much lower frequency (60 to 70 kHz) with adequate performance.

3.2 Tag Signals and Receivers

The simplest tags produce a continuous wave (CW) at a set frequency but are expensive on battery power and have a short life. They can only be located by triangulation using two trainable narrow beam receiving hydrophones. Frequency modulated (FM) CW tags can be used to transmit information, however, and this is the principle means by which physiological and environmental measurements are telemetered from free swimming fish. For example the electrocardiogram (ECG) of a fish can be detected by implanted electrodes and used to modulate a CW tag.

Most acoustic tags produce an interrupted or pulsed signal and are commonly known as "pingers". They typically produce short bursts of ultrasound a few milliseconds long about once every second or so. Compared with CW tags, there is a large saving in battery power by virtue of the short duty cycle. In order to accommodate the short pulses, receivers are required with a wider bandwidth than comparable CW receivers. Pulsed transmissions can also be used to send identification and other information by pulse code modulation (PCM) and other encoding techniques (Bagley [18]) but at longer ranges, these often fall foul of the difficult propagation conditions frequently found in the sea. Pulsed transmissions also lend themselves to tracking systems where the transit time from transmitter to receiver is used to determine range and position. Transponding tags have the advantage that they provide immediate range and bearing information when used with a sonar.

In some studies where fish move between sea and fresh water a combined acoustic and radio transmitter (CART) has been employed (Potter *et al.*, [28]) so that adult salmon, for example, tagged at sea can be tracked as they swim through the estuary into freshwater.

Bandwidth limitations and propagation difficulties can not be easily overcome by using complex transmission modes. Sophisticated methods of generating acoustic signals such as multi-frequency, digital, frequency-shift keying (FSK) can now reliably transmit complex data over long distances in the sea but the necessary circuitry and transducers could not be accommodated at present in miniature devices intended for attachment to fish.

3.3 Physiological and Environmental Telemetry Tags

The signal from acoustic transmitters can provide positional information but fitted with specialised sensors a variety of physiological and environmental information may be relayed. Although some of the sensors have been developed for use with radio-transmitters in freshwater the same sensor may be employed to modify the output signal of an acoustic tag. Parameters such as activity

ACOUSTIC TRACKING OF FISH IN THE SEA: CURRENT STATUS AND FUTURE PROSPECTS

(Young *et al.*, [29]; Ross *et al.*, [35]; Johnstone *et al.*, [36]), heart-rate (ECG) (Armstrong *et al.*, [37]), electromyograms (EMG) from swimming fish (Ireland & Kanwisher, [38]), pressure as an indication of depth (Stasko & Rommel, [39]; Westerberg, [40]), salinity (Priede, [41]), temperature (Hawkins & Urquhart, [7]) and oxygen content of the water (Priede *et al.*, [42]) have been transmitted from tags in studies with freshwater and marine fish.

Miniaturisation of sensors and sensor power requirements impose severe limits on the development of telemetry tags. For some applications researchers are turning to data storage tags which do not transmit an acoustic signal.

4. DISCUSSION

4.1 The Limitations of Active Sonar Systems

Some of the shortcomings of active sonar for the study of fish behaviour have already been described in section 2.1. Sophisticated sonars capable of resolving individual fish are very expensive and need ships to carry them. None of them has been specifically designed for tracking and, with the exception of the Admiralty Research Laboratory (ARL) scanner (Mitson & Storeton-West, [13]) and similar sector scanning sonars, any tracking capability is usually secondary to their main function which is usually the location and capture of fish schools or the measurement of fish abundance. It is usually extremely difficult to manoeuvre a large ship in order to keep in contact with individuals. At short range there is always a danger of disturbing the fish and the low frequencies required to work at long range would be less effective in resolving individuals. It is significant that most of the studies using active sonar have been concerned with the effects of ship disturbance and reactions to towed fishing gear.

A major advance would be the development of a long range sonar, specifically designed for fish tracking purposes, which did not significantly compromise the ability to resolve individual targets. It would need to operate at a frequency or frequencies to suit a range of transponders and have automatic target tracking with a narrow beam to allow the tracking vessel to stand off at a distance of several hundred meters. Mounted in a manoeuvrable, quiet vessel and linked to modern navigational equipment such a sonar might allow truly long-term open-sea tracking.

4.2 The Limitations of Passive Sonar Systems

Most problems with fixed array systems arise from poor propagation conditions which can result in ambiguities in position determination. Acoustic signals can also be disrupted when tagged fish are screened by sea bed features or take refuge in rock crevices or vegetation. This problem is reduced when tracking with a mobile system from the surface, but the precision of data collected with a fixed array system is usually far superior. Modifying the hydrophone array system described in section 2.2.1 to transmit data by radio to the processing equipment instead of relying on direct cable connection would be a practical improvement.

Mobile passive sonar used to track fish fitted with pingers is generally fairly crude often consisting simply of a hand held directional hydrophone and a receiver carried in a small boat (Fig. 6). This method has, nevertheless produced more useful data on fish movements than most active sonars, however complex. Operators can keep in intimate contact with a fish and respond quickly to any change in its activity but the method is often arduous and can not be sustained for very long. A fish tracking sonar with some of the features described in section 4.1 above, operating in passive mode, could allow fish to be studied over longer periods.

Another possibility is to adopt a search strategy instead of attempting to maintain contact with individual tagged fish. Once a batch of fish are tagged and released the tracking vessel could conduct a search pattern based on predicted fish positions calculated from estimated swimming speeds. Regular surveys could then be conducted to determine the distribution of tagged fish. Individually identifiable tags would be an advantage for this application.

4.3 Acoustic Tags - Problems and Compromises

4.3.1 Tag Size and Output Power. Although the conflicting requirements and trade-offs of tag design are well understood, marine biologists continue to seek two important developments; greater range from existing tag sizes and much smaller tags with good output for attachment to juveniles and small species. An increase in detectable range can only be achieved by reducing the frequency or by increasing the acoustic power output. Reducing the frequency results in increased size as already discussed and this is often unacceptable. Increased output can theoretically be achieved by increasing the voltage across the transducer. This would require more turns on the transformer secondary winding. The transducer and transformer are, however, major elements of the resonant circuit and any alteration away from resonance produces a decreased output. The best acoustic tags are, in short, optimised within practical limits for the best possible output from a particular transducer.

An analysis of the energy budget of a typical acoustic tag is given in Appendix I. This indicates that there may still be room for some improvement but it will not be easily achieved. It will require a radical change in transducer design, perhaps a new material, to achieve more efficient conversion of electrical energy and higher output levels. The advent of lithium batteries has brought great benefits to tag design but the battery is still the single largest and heaviest component. Further developments in battery technology or some new alternative power source may bring further benefits in future.

4.3.2 Biological Effects of Tags. Laboratory studies of feeding behaviour have demonstrated that intragastric tags (ie, inserted through the mouth into the stomach) do not affect the quantity of food consumed by cod, *Gadus morhua* L., (Lucas & Johnstone [43]) but Armstrong & Rawlings [44] report that stomach insertion of transmitters should be used with caution for Atlantic salmon parr. The use of intragastric tags in studies with salmon smolts (McLeave & Stred [45]) and adults (Stasko [27]), however, does not appear to affect the behaviour of the fish adversely. A successful surgical implantation technique for juvenile salmon, where the tag is inserted into the peritoneal cavity through a small incision which is then closed with sutures, has been described by Moore *et al.*, [33]). Internal placement has certain advantages over external attachment. The tag can not snag on obstructions, is invisible to predators and the risk of tissue damage and infection at the attachment site is avoided.

Although it is possible that transmitter beam patterns may be affected by the gas-filled swimbladder (Fig. 8), in practice, there has been no noticeable difference in signal strength between internal or externally attached acoustic tags (personal observation).

ACOUSTIC TRACKING OF FISH IN THE SEA: CURRENT STATUS AND FUTURE PROSPECTS

4.3.3 Physical Effect of Tags on Fish. Whether tagged internally or externally a fish will be affected both by the weight of the tag and by its mass. Tags are normally constructed so that they are almost weightless in sea water or slightly heavy. A weight in sea water of two or three grammes is common and this is normally small in comparison to the weight of the fish. Species with swimbladders can easily compensate for the added weight (Fried *et al.*, [46]). Where necessary, additional buoyancy can be added to the tag but only at the expense of extra mass, volume and drag.

All tags, including weightless and internal tags, add mass to the tagged fish. This is of little consequence to a static or slow moving animal but any burst of speed will cost the fish additional energy to accelerate the extra mass and give it added momentum when moving. External tags impose an additional constraint on mobile fish in the form of hydrodynamic drag. Both drag and momentum are proportional to the square of velocity so these effects increase rapidly with increasing speed but in proportion to the animal's own body drag and momentum. There is therefore a fundamental need to keep tag mass as low as possible and externally attached tags need to be shaped to give the lowest possible coefficient of drag. The volume occupied by an internal tag needs to be kept to a minimum.

External attachment methods are illustrated by Hawkins & Urquhart [7] and the effects of carrying external acoustic transmitters on the swimming performance of plaice and cod have been discussed by Arnold & Holford [47]. For smaller fish, "pannier" tags, where the electronics package is encapsulated separately from the battery pack and arranged to straddle the fish's back (Fig. 7), allow the weight of the transmitter to be more evenly distributed than that of a more conventional single package (Young *et al.*, [29]; Thorpe *et al.*, [30]).

4.3.4 The Effect of a Tag's Acoustic Output on Fish. The results of control experiments carried out with groups of tagged and untagged fish show no evidence of any reaction to the tag's acoustic output. Sound playback experiments, often involving the fish being trained or conditioned to respond in a unequivocal way to sounds, indicate that they are sensitive to low frequency sounds, generally below about 1 kHz and with rapidly declining sensitivity above this value. Many observers, however, have reported fish apparently reacting to echo sounders and recent investigations by Astrup & Mohl [48] conclude that cod can detect very intense levels of 38 kHz ultrasound with a mean threshold level of 194.4 dB re 1μPa. Fish have no known sensory organs capable of detecting ultrasound but there is usually a very low intensity, low frequency component of sound inherent in the short pulses produced by ultrasonic fish tags and there are a number of mechanisms by which intense ultrasonic energy can be converted, in part, into small amounts of acoustic energy in the audio range. Some pulsed ultrasonic fish tags can sometimes be heard, though only just, by holding them in close contact with the human ear.

The most powerful acoustic fish tags have a source level of about 163 dB re 1μPa which means that, according to Astrup & Mohl [48], placed near a cod at a distance of about 3 cm the hearing threshold level would be reached and the tag would just be detected. Whether carried externally or implanted, the distance from the acoustic centre of a tag to the main hearing organs is usually greater than 3 cm even with the smallest fish capable of carrying such a tag. The transducer end of the tag is normally furthest away from the fishes hearing organs (Fig. 8). In addition, many acoustic tags operate at frequencies above the 38 kHz investigated by Astrup & Mohl [48] where the threshold level might be expected to be higher.

Our conclusion is that tagged fish may just detect the acoustic output from an ultrasonic pinger but the signal will be close to the threshold of detection and may be masked by the levels of ambient noise which often prevail - especially in the sea. A far more significant problem when fish are being tracked from a vessel is the effect of noise from the tracking vessel itself. Fish are acutely sensitive to the direction of low frequency sound sources, and may well take action to avoid the noise generated by a manoeuvring boat.

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ACOUSTIC TRACKING OF FISH IN THE SEA: CURRENT STATUS AND FUTURE PROSPECTS

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ACOUSTIC TRACKING OF FISH IN THE SEA: CURRENT STATUS AND FUTURE PROSPECTS

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APPENDIX I

An Approximate Analysis of the Energy Efficiency of a Typical Acoustic Tag

A typical acoustic tag is powered by a 3.5 V lithium battery of nominal capacity 850 mAh.

Total energy available from battery = 3.5 X 0.85 = 2.975 Wh.

Assume an acoustic power output of 0.5 W (approximately 168 dB/µPa).

Then equivalent continuous operating life = 2.975/0.5 = 5.95 h.

For a pulsed tag producing a pulse of 2 ms duration once per second this notional duration could be increased by a factor of 1000/2 ie duration of pulsed tag = 2975.0 h.

This figure is much greater than can be obtained in practice for three main reasons:-

1. The battery capacity is quoted for optimum discharge conditions but in acoustic tags current must be delivered in short intense bursts at low temperature which will reduce the available energy. Also there will be some fall in the output voltage particularly near the end of battery life thus reducing the capacity calculated from nominal figures.

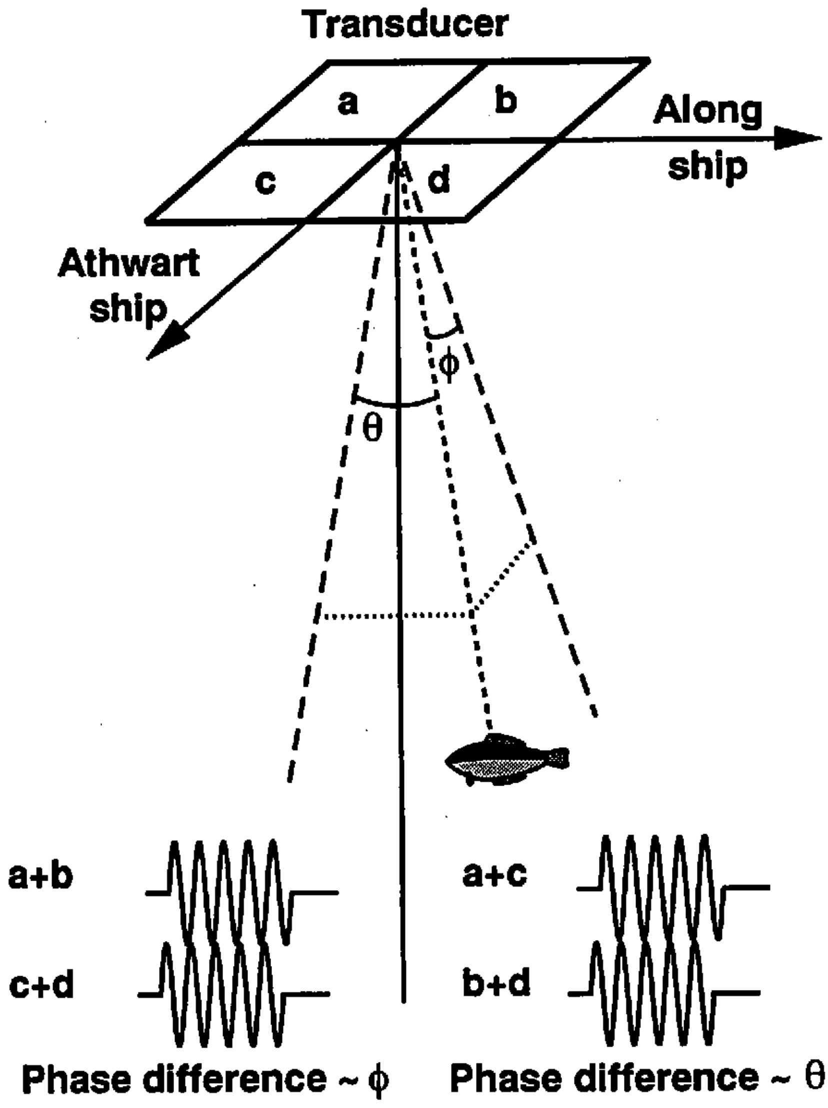
2. Some of the battery energy will be dissipated as heat through electrical losses in the tag circuitry and particularly in the transformer windings.

3. Further losses will occur in the transducer which will not be capable of converting all the electrical energy delivered to its terminals into acoustic energy radiated out into the water.

In practice, an operational life of 700 or 800 h can be obtained from typical tags using the type of battery on which this analysis is based.

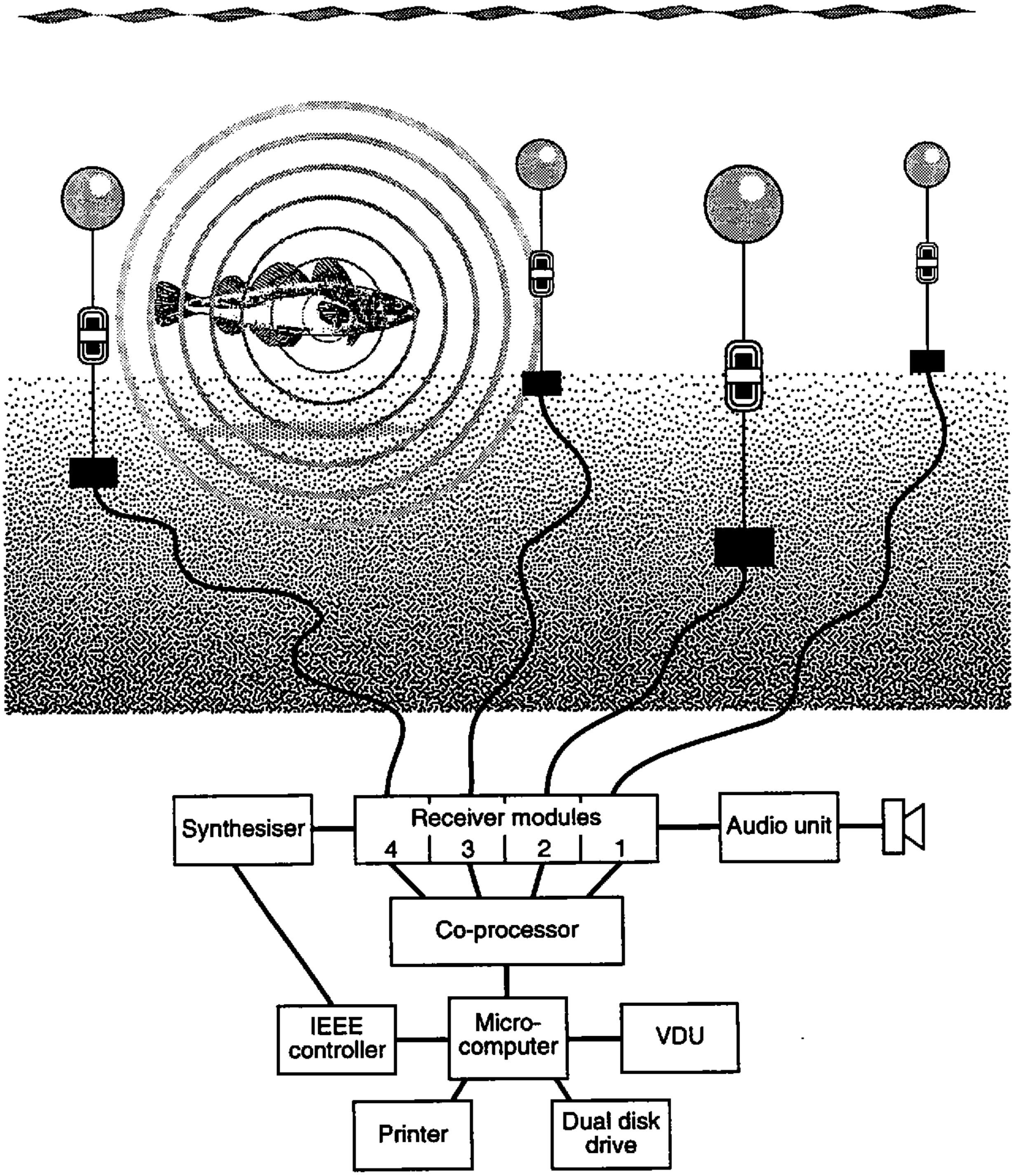
This would suggest an overall efficiency in energy terms of about 25 %.

Figure 1. Principles of the split-beam echo sounder



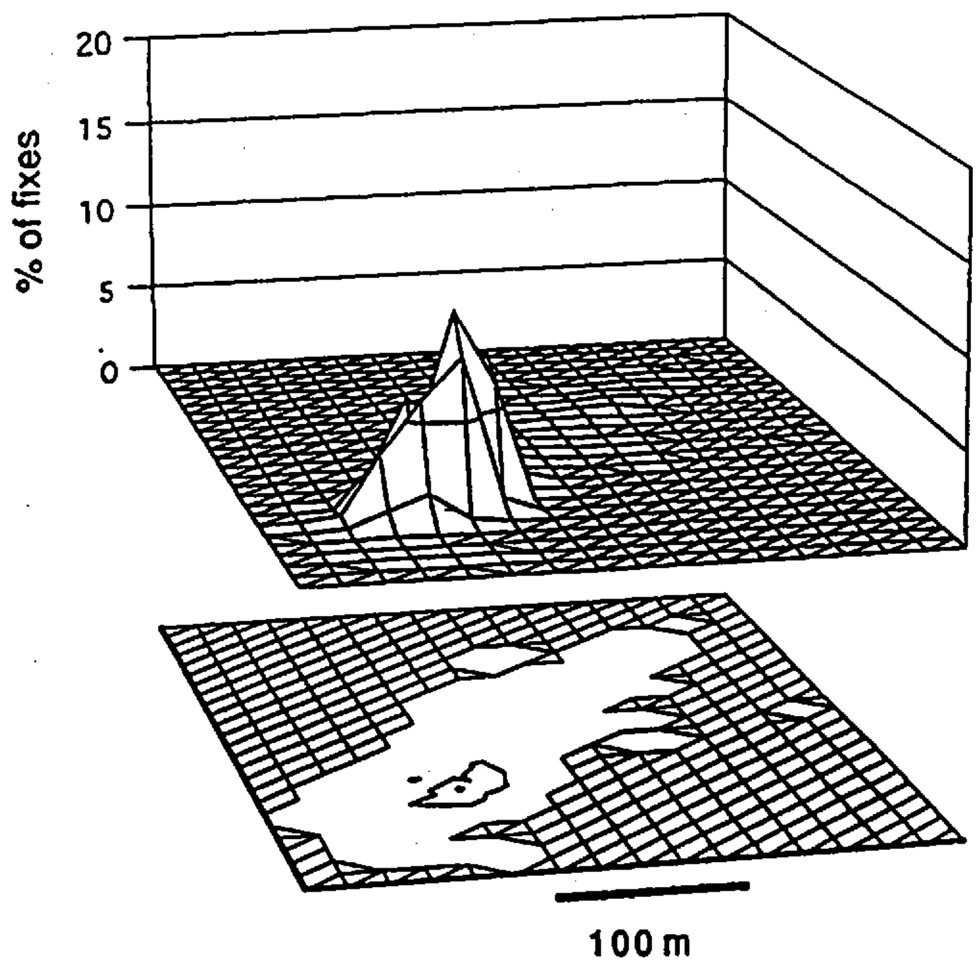
The transducer is divided into four equal quadrants. The transmission pulse is applied to the whole transducer but the return signals are received by the four quadrants and processed separately. Differences in the phase angle of signals received are combined as shown and used to determine the target direction. This enables the range and bearing angle of targets within the beam to be measured and the horizontal position of individual fish in different depth layers to be tracked simultaneously. (After MacLennan & Simmonds [49]).

Figure 2. A hydrophone array system for underwater acoustic tracking



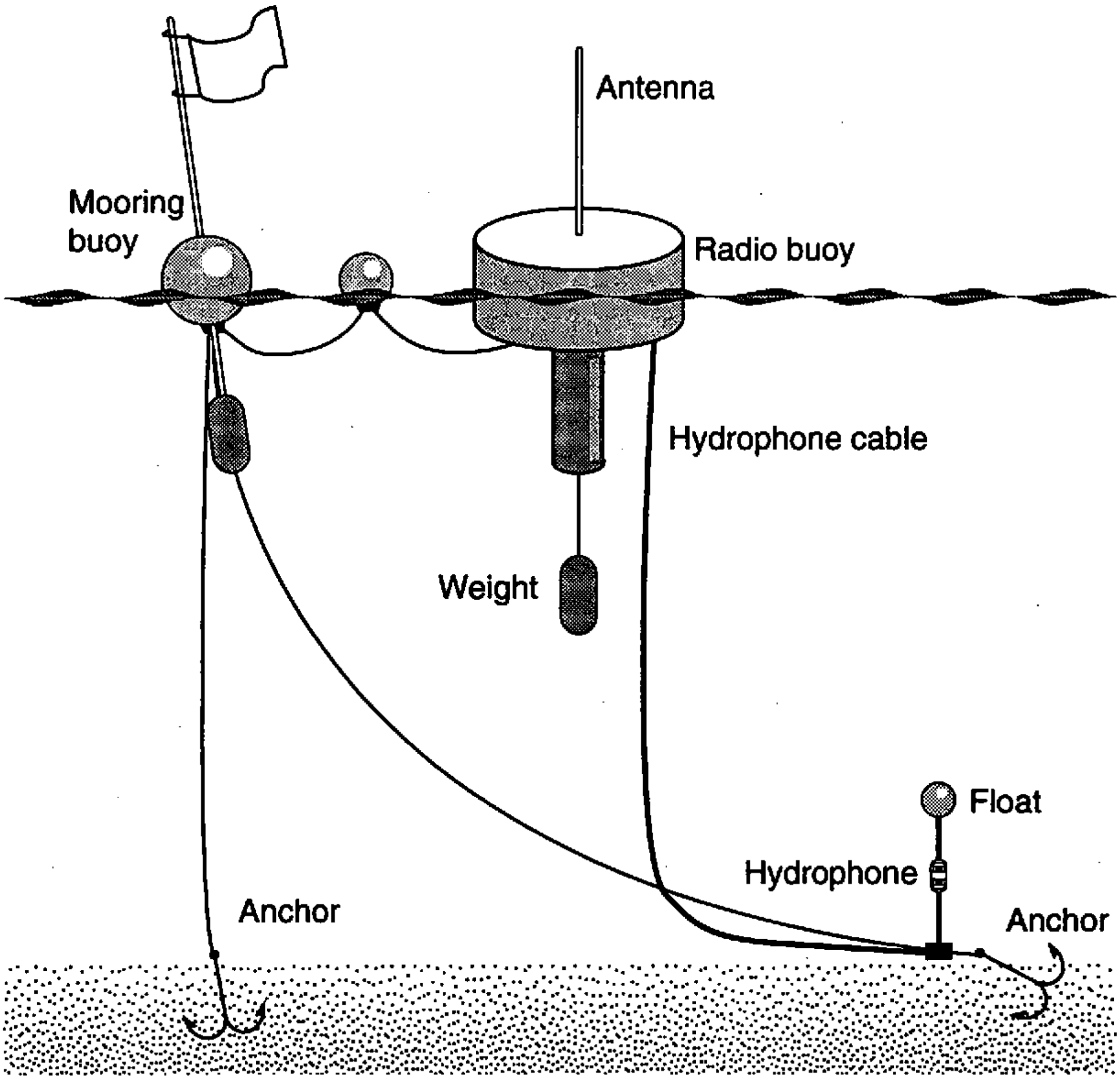
A schematic diagram of a fixed hydrophone array acoustic tracking system and a saithe, *Pollachius virens*, fitted with an internal ultrasonic transmitter. Four hydrophones and receiving units are shown but up to seven can be connected at a time.

Figure 3. Fish movement data obtained using a fixed hydrophone array



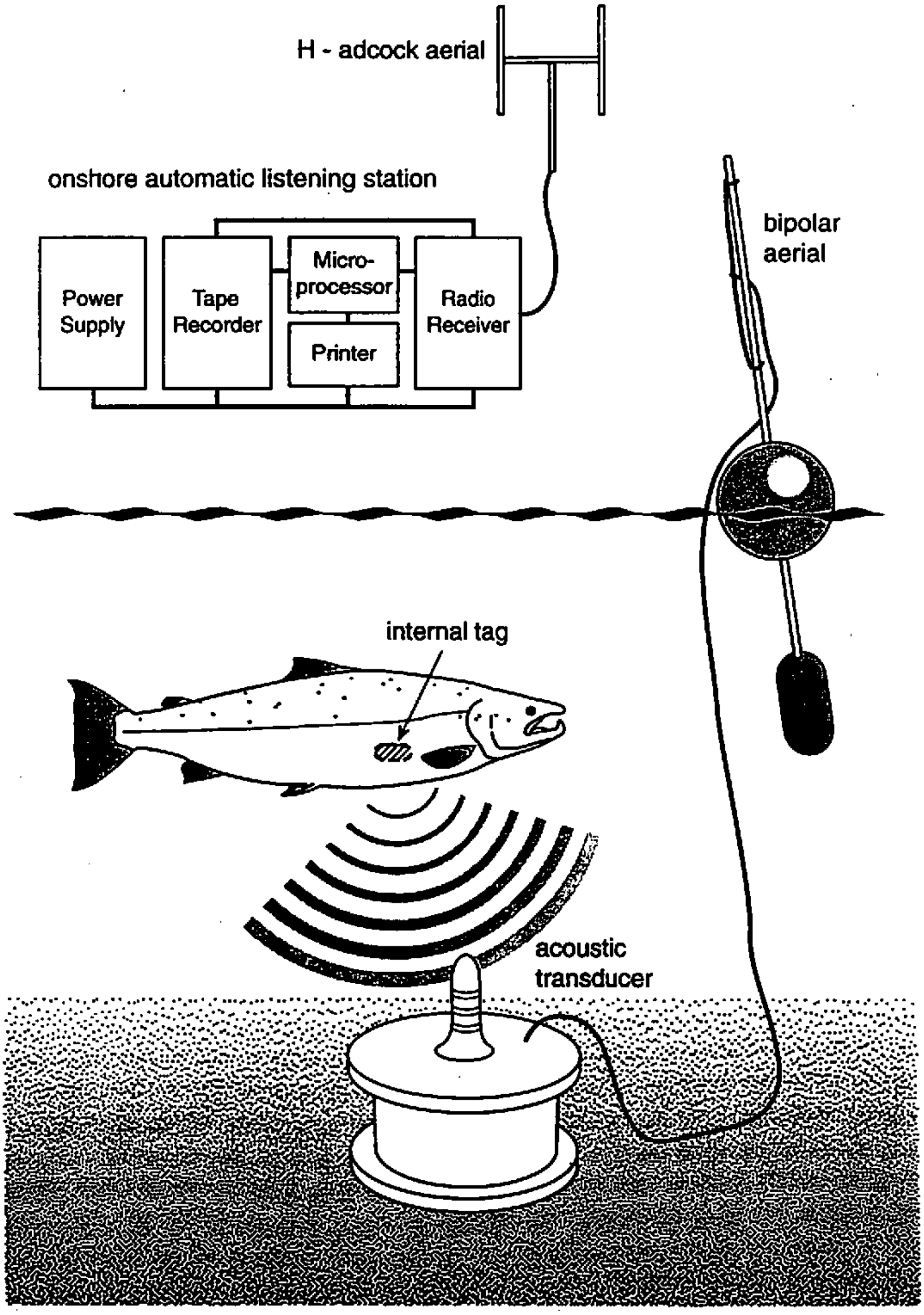
The home range of a saithe, *Pollachius virens*, tracked for more than 24 h. The contour plot shows the pattern of occupation, and contour values show percentage of overall fixes. (After Glass *et al.*, [20]).

Figure 4. A marine radio link tracking system



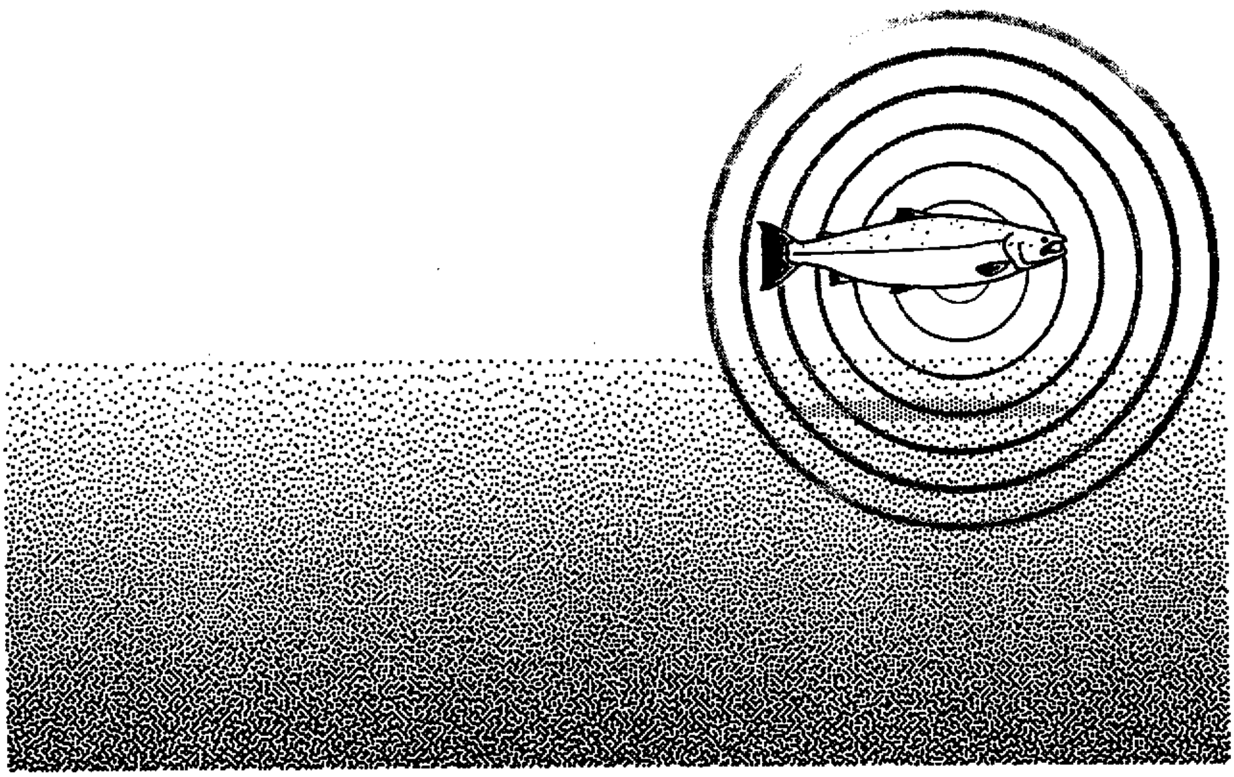
A diagram of the positioning system (VR-20 Buoy Positioning System, VEMCO Ltd, Halifax, Canada) which has been deployed during Norwegian research into the movements of fish and shellfish fitted with acoustic tags. (After Bjordal *et al.*, [23]).

Figure 5. An estuarine sonar buoy system



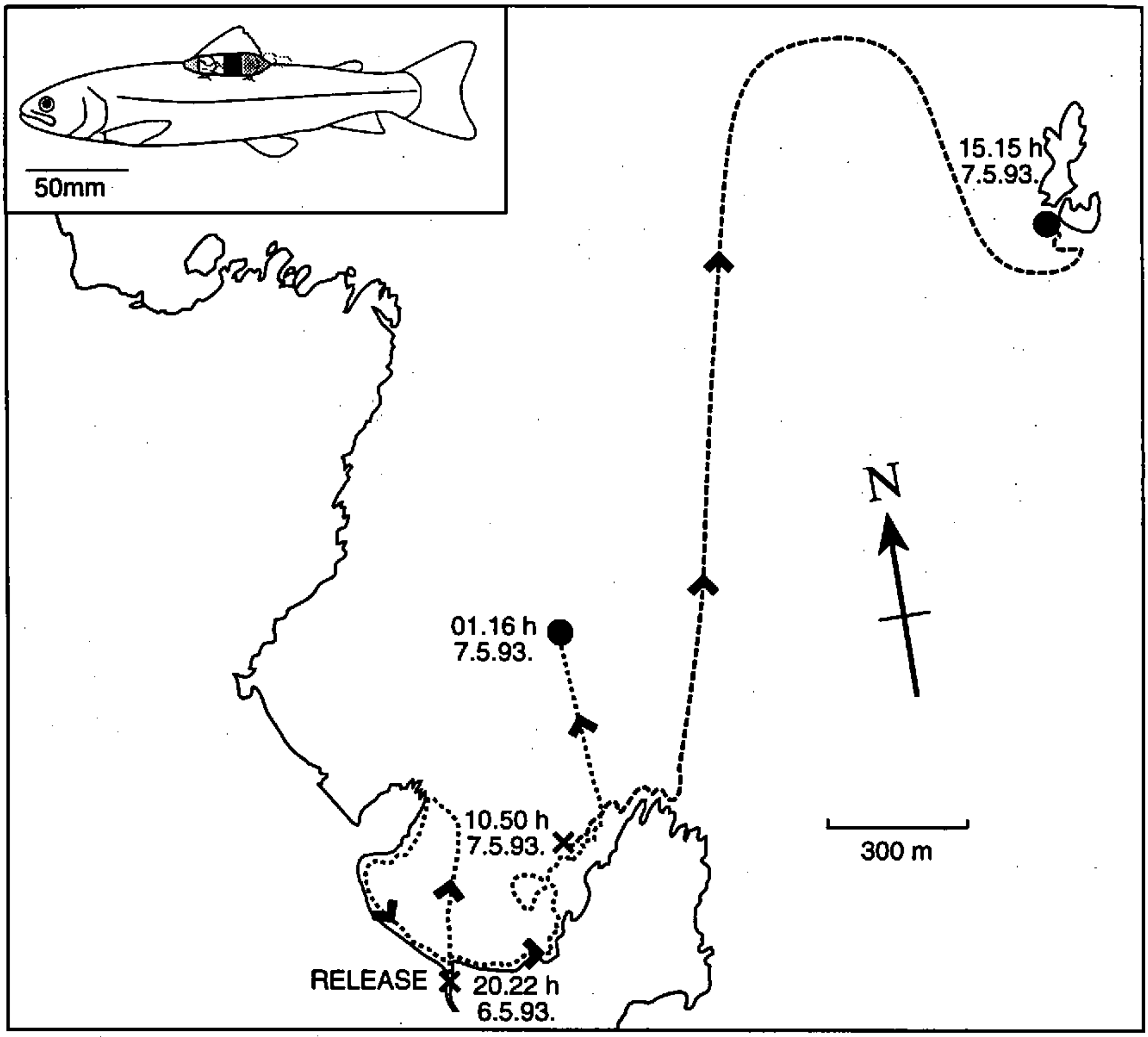
A diagrammatic representation of a sonar buoy designed by MAFF Fisheries Laboratory Lowestoft. A salmon fitted with an internal ultrasonic tag is shown in proximity to the underwater acoustic transducer. The sonar buoy transmits a radio signal via a bipolar aerial at the surface which corresponds to the repetition rate of the acoustic tag. The signal is then detected by a remote microprocessor controlled automatic listening station which can record the event together with time, date and channel number.

Figure 6. Fish tracking from a small boat



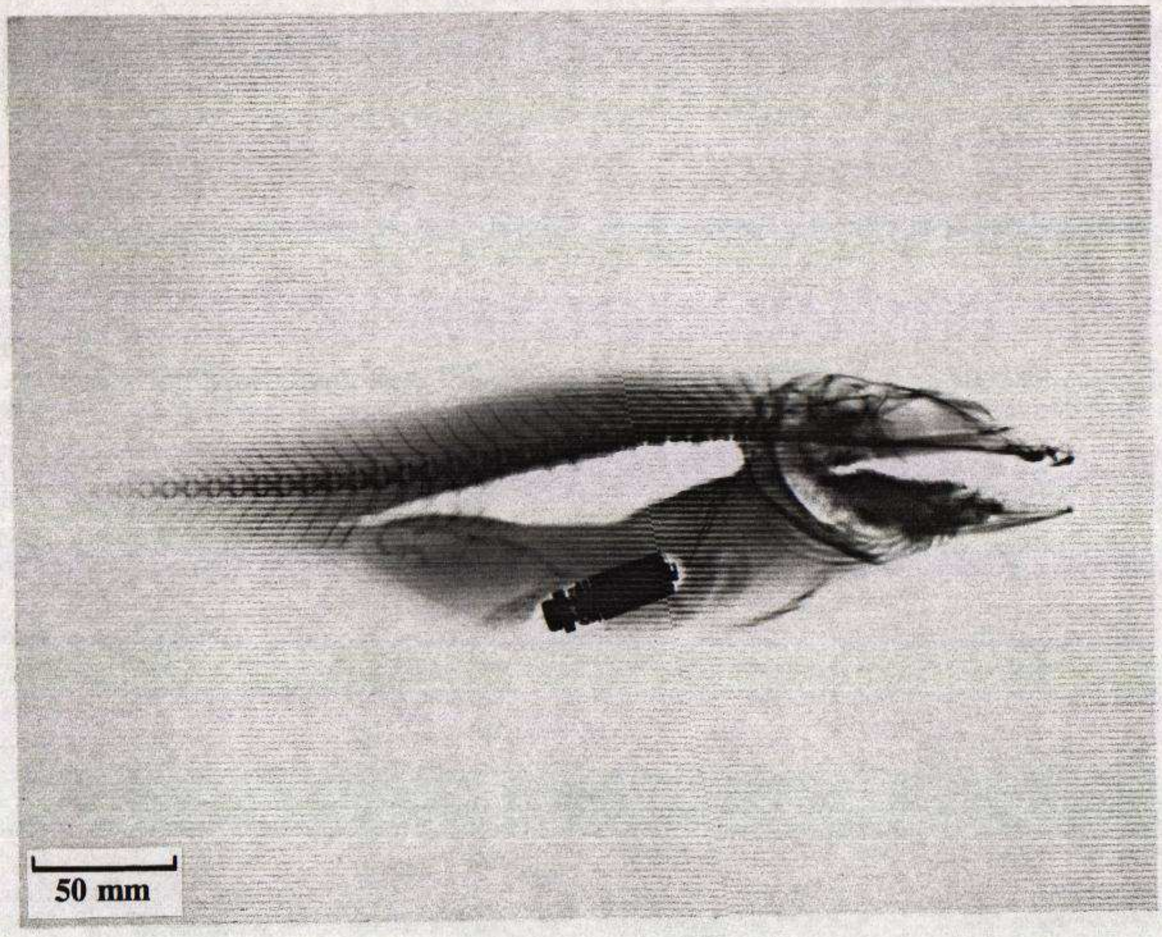
Acoustic tracking of a tagged salmon in the sea with a portable, battery powered ultrasonic receiver and directional hydrophone. While at sea, a "mother" ship can maintain contact with the tracking vessel to determine position and collect relevant environmental information.

Figure 7. Sea trout smolt movements



The track obtained from an emigrating sea trout smolt as it first entered the sea from the River Squod into Loch Ewe, on the west coast of Scotland. A miniature 70 kHz ultrasonic "pannier" tag was attached externally to the fish (see inset). Note that the battery pack attached to the other side of the fish is not shown. After release at 20:22 h on 6 May 1993 the smolt was actively tracked from a small inflatable boat, at a maximum range of approximately 150 m, until tracking ceased at 15:15 h the following day.

Figure 8. Radiograph of a tagged cod



A lateral radiograph of a cod, *Gadus morhua*, with an intragastric acoustic tag. The overall length of the transmitter is 56 mm. The swimbladder is the white area immediately above the transmitter.