Acoustic tracking

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Abstract

Acoustic tags are used to track marine fish because, unlike radio waves, sound propagates well in salt water. Simple 'pingers' transmit at regular pre-set intervals; transponders transmit on receipt of an external signal. Both types of tag can be used to telemeter physical or physiological data. The diameter of the tag and detection range both vary inversely with operating frequency, which ranges from 30 to 300 kHz. Tags can be attached externally, surgically inserted in the peritoneum, or ingested voluntarily. Fish tagged with acoustic tags can be tracked with a fixed hydrophone array or a series of moored buoys, from which data can be recovered by radio or satellite. High-resolution systems can be used to track the small scale of movements of fish in the vicinity of dams or barrages. Mobile tracking systems range from small boats fitted with rotatable, directional hydrophones to large research vessels towing a hydrophone array, or fitted with a sector scanning sonar. These tracking systems are labour intensive and development is increasingly towards automated listening stations or data storage tags, which record information at equivalent rates but avoid the need to follow the fish continuously for long periods, and remote data retrieval by satellite.

Introduction

Acoustic tags (30-300 kHz) are used to track marine fish because sound propagates well in salt water, whereas radio waves are rapidly absorbed (e.g. Niezgoda *et al.* 1998). Acoustic tags can also be used in freshwater, if there is no aeration. In this paper acoustic tags and tracking systems are described first, followed by discussions on tracking fish in the open sea and in estuarine and coastal waters.

Acoustic tags and tracking systems

Types of tag

Simple 'pingers' transmit regularly and continuously, whilst transponders transmit on receipt of an external signal. Both can be used to telemeter environmental data, such as pressure, temperature, and light intensity, or physiological data, such as heart rate, respiration rate and body temperature (e.g. Priede 1992). Tags can be individually coded by modulating frequency or pulse repetition rate and this permits groups of fish to be followed at the same time. Coding with pseudo random (PN) numbers, a recent development, allows large numbers of fish to be tracked simultaneously (Cote *et al.* 1998; Voegeli *et al.* 1998).

Operating frequencies

Acoustic tags emit ultrasonic frequencies, which are usually produced by driving an annular ceramic transducer at its resonant frequency. Tag size is governed by the size of the transducer, whose diameter is inversely proportional to frequency (Priede 1986). Range also varies inversely with frequency, so that, whilst a large diameter 32 kHz tag may have a range of as much as 2.5 km (Klimley *et al.* 1998), a small 300 kHz tag usually has a range of less than 400 m. Frequencies of 30-50 kHz are used for tracking large pelagic fish in the open ocean; frequencies of 60-80

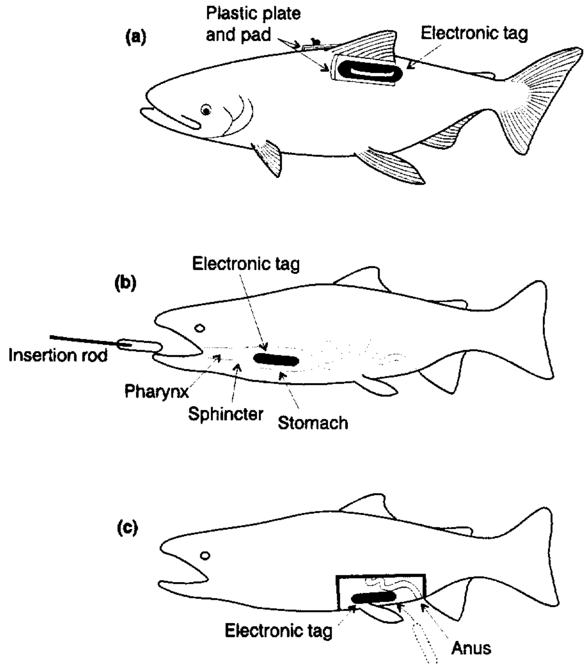

Figure 1. Methods of attaching acoustic tags to salmonid fish: (a) external; (b) stomach; and (c) peritoneum (redrawn from Mellas and Haynes 1985). Similar techniques are used for other types of fish (see e.g. Anon 2000).

kHz are commonest in coastal and estuarine waters (Priede 1992). A frequency of 75 kHz, with a typical working range of one km, is popular for use with coastal and freshwater fish. Higher frequencies of 150-300 kHz are used where a small tag is required (Priede 1992), or where specialised high-frequency imaging sonars are available (Arnold *et al.* 1990). Physical constraints on acoustic signal propagation and detection are discussed by Priede (1992) and Voegeli and Pincock (1996).

Tag attachment

Acoustic tags are attached to fish in a variety of ways, either internally or externally (Figure 1). External tags are commonly attached at the base of the dorsal fin with non-corrosive wires or threads inserted through the dorsal muscles. A compressible pad is often used to protect the skin of the fish. Internally tags may be put inside the stomach or inserted into the peritoneum after surgery. Voluntary ingestion in bait is another common approach (e.g. Løkkeborg 1998).

Tracking systems

The simplest tracking system, which consists of a directional hydrophone, a receiver and headphones, allows the operator to follow the tagged fish and obtain an approximate estimate of its position relative to the boat (e.g. Holland *et al.* 1985). Accurate location, however, requires a hydrophone array, or active sonar. Mobility to equal that of a free-ranging fish is achieved with a research vessel (e.g. Arnold *et al.* 1990). Weather permitting, a large research vessel can track an individual fish until the tag batteries are exhausted, usually after 10-15 days at most. With a small boat, track duration is primarily limited by human endurance (Nelson 1978), although autonomous vehicles may perhaps overcome this limitation in future (Goudey *et al.* 1998).

Tracking fish in the open sea

There have been many fish tracking studies in the sea since Yuen (1970) first followed a skipjack tuna in Hawaiian waters. These have recently been reviewed by the CATAG working group in Europe (Anon 2000) and further information can be found at http://www.hafro.is/catag.

Ship-mounted and towed hydrophone systems

Most marine fish tracking has been carried out with small boats using a directional hydrophone (e.g. Lawson and Carey 1972) attached to a long retractable pole. The hydrophone is deployed at a depth of 1.5 to 3 m below the surface and is usually contained in a streamlined housing, which permits acoustic tags to be detected at speeds up to 7 knots (e.g. Stasko and Polar 1973; Holland *et al.* 1985). The retractable pole can be fitted to a block clamped to the gunwale (Nelson 1978) or mounted in a special bracket attached to the side of the boat (Holland *et al.* 1985, 1992). Another option is to use a fared shaft on the bow (Stasko and Polar 1973; Carey and Robison 1981), although bow-mounted hydrophones are more susceptible to movement than those on the side of the boat (Jolley and Irbey 1979).

The hydrophone can be fixed facing forwards and the tag located by turning the boat (Jolley and Irby 1979; Holland *et al.* 1985). Alternatively, the hydrophone may be rotated by hand to locate the tag and detect the direction of maximum signal strength (Lawson and Carey 1972; Carey and Lawson 1973; Holland *et al.* 1992). Rotating hydrophones have also been used on larger research vessels (~25-50 m), either attached to the side of the vessel (Ogura and Ishida 1992) or mounted under the hull (Tesch 1974; Block *et al.* 1992).

After release, the tracking boat follows the tagged fish, keeping the acoustic tag within audible range. Because it is not possible to measure the range of the tag with a single hydrophone, it is assumed that the track of the fish is the same as that of the boat, whose position is plotted from visual landmarks, a radio navigation system (e.g. Loran or Decca), or GPS. More accurate fish tracks can be obtained with a towed hydrophone system, such as the VR28 Tracking System (Vemco Ltd, Nova Scotia, Canada), which can measure the range and bearing of the acoustic tag with a micro-controller receiver and four independent acoustic receivers (aligned ahead, astern, port and starboard). Block *et al.* (1997) report detection ranges of 0.8 to 1 nautical mile when using this system to track yellowfin tuna in the eastern Pacific with 34 and 50 kHz transmitters.

Sector scanning sonar and transponding acoustic tags

The Lowestoft Laboratory uses high-frequency, high-resolution sector scanning sonar (Voglis and Cook 1966; Mitson and Cook 1971) and transponding acoustic tags (Mitson and Storeton West 1971) to track fish at sea. The sonar, which produces acoustic pictures of the seabed and other underwater targets such as trawl gear (Cushing and Harden Jones 1966), insonifies a 30° x 10° beam (Figure 2) with a 2 ms pulse of sound at rates of 2 or 4 pulses s^{-1}. The beam is scanned electronically at 10 000 Hz. Range and bearing resolution are 20 cm and 0.33°, respectively, although during tracking the position of the fish is estimated only to the nearest 5 m and 1°. The sonar transducer is hydraulically stabilised against roll, pitch and yaw and can be steered in azimuth to observe all round the ship. Tilt angle can be varied continuously from vertical to horizontal. The sonar can be quickly switched from horizontal (Figure 2a) to vertical mode (Figure 2b) to estimate the depth of the target (Greer Walker *et al.* 1978). Depth estimates are quite good (± 0.5 m) at close range but increase significantly at longer distances (Arnold and Greer Walker 1992).

Transponding acoustic tags, which transmit a 3 ms pulse of sound when insonified by the sonar (Mitson and Storeton West 1971), can be detected out to ranges of about 600 m under ideal conditions. Fish are, however, normally tracked at ranges between 120 and 250 m (Arnold *et al.* 1994). The fish track is plotted electronically, using the range and bearing of the fish estimated from the sonar display, and the position of the ship determined by GPS. The original acoustic tag, whose dimensions were 50 x 10 mm, had negligible drag (Arnold and Holford 1978) but an

Figure 2a

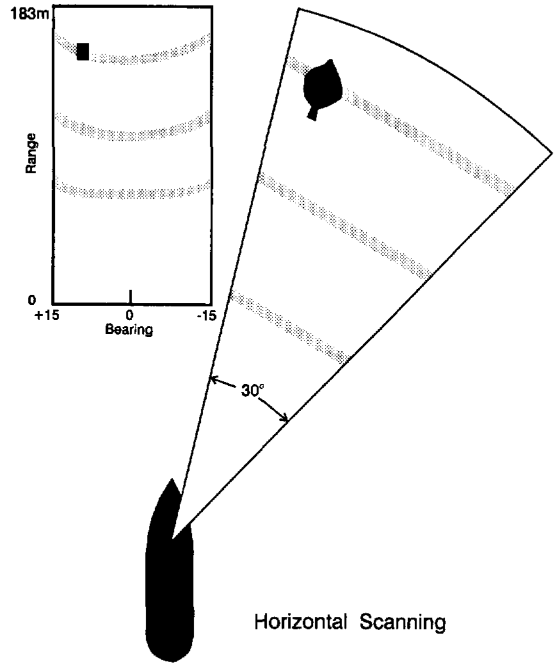

Figure 2b

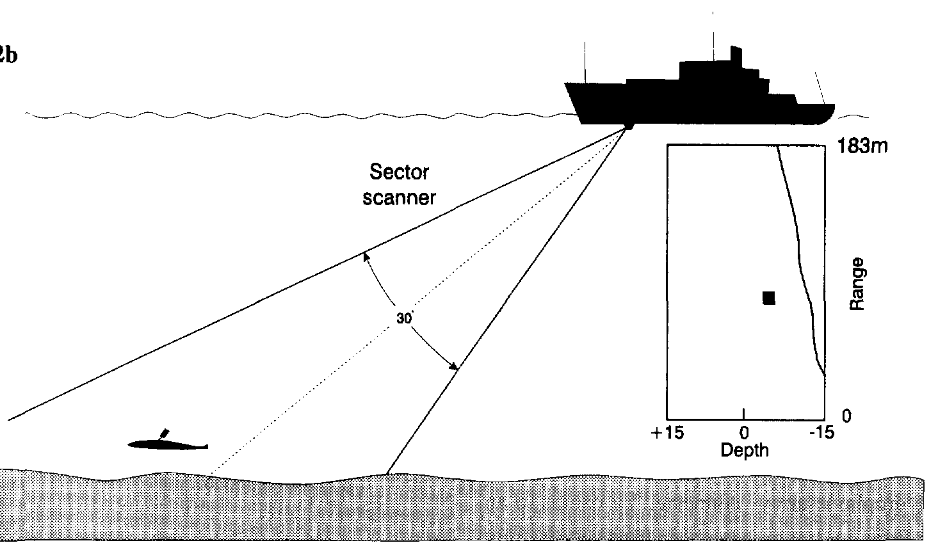

Figure 2. Tracking fish in the open sea using transponding acoustic tags and 300 kHz sector scanning sonar in (a) horizontal and (b) vertical mode. The range and bearing of the fish are measured in horizontal mode. Depths are estimated in vertical mode from slant range and the tilt angle of the transducer when first the tag signal and then the bottom signal are brought on to the centre line of the B-scan display (see insert). For further details see Greer Walker *et al.* (1978) and Arnold and Greer Walker (1992).

operating life of only about 2-3 days. The tag we currently use is larger (60 x 15 mm), has bigger batteries and a life of about 10 days, which can be increased by transmitting alternate pulses of sound with the sonar.

Automated listening stations

Simple listening stations have been developed to investigate the seaward movements of wild Atlantic salmon smolts in coastal waters of eastern Canada (Voegeli *et al.* 1998). Smolts marked with small (single-chip) acoustic pingers and released in freshwater are detected by chains of self-contained underwater receivers moored in the passages between Passamaquoddy Bay and the Bay of Fundy. Tidal currents are strong in these passages and water depth ranges from 50-150 m, creating a hostile environment for fish tracking. The system uses single channel receivers and miniature transmitters, which contain a micro-controller and transmit a complex six-pulse code capable of identifying 4 096 different fish on the same frequency.

Several groups of fish, including sharks and tunas, regularly return to the same location (e.g. Klimley and Holloway 1999) and this behaviour raises the prospect of setting up long-term listening stations with fully automated acoustic systems capable of downloading data and re-programming tags attached to returning fish. Preliminary trials with tiger sharks (Klimley *et al.* 1998) suggest that such systems could be practical in certain conditions.

Sonar buoys with radio transmission of data

Fixed hydrophone arrays connected by cables to an onshore listening station have been used successfully in confined coastal waters (e.g. Glass *et al.* 1992) but are not practical in open waters. The concept has, however, been extended to the open sea with the use of sonar buoys, which can convert acoustic signals to radio signals and transmit them to a ship, or shore-based listening station (e.g. Engås *et al.* 1996; Løkkeborg 1998). At least three buoys are required, moored 400-600 m apart in a triangular configuration; four buoys can provide three-dimensional information on the position of the fish (Voegeli and McKinnon 1996). Commercial sonar buoy systems are manufactured by Vemco Ltd (Shad Bay, Nova Scotia, Canada) (e.g. O'Dor *et al.* 1998) and Lotek Engineering Inc. (Newmarket, Ontario, Canada) (e.g. Cote *et al.* 1998).

Deep-sea tracking systems

Scientists at Aberdeen University in Scotland have developed an autonomous free-fall acoustic tracking vehicle capable of following the movements of abyssal scavengers, such as grenadiers (*Coryphaenoides* spp.), in the deep ocean (e.g. Armstrong *et al.* 1992). In its latest version, the AUDOS (Aberdeen University Deep Ocean Submersible) vehicle, which is capable of operating at depths down to 6 000 m, carries a scanning directional sonar, as well as a camera, flash unit, electromagnetic current meter, compass, micro-controller and batteries (Bagley and Priede 1996). Fish are tagged with ingestible code-activated transponding (CAT) tags, operating at 77 kHz (Bagley 1992). The tags (65 x 12.5 mm), which transmit a single return pulse on receipt of an individually recognised pulse code, can be detected out to a range of 500 m with a precision of 0.5 m.

Tracking fish in estuarine and coastal waters

Research vessels are often too large for confined waters, where tracking is better carried out with small boats, or moored sonar buoys, which convert acoustic signals to radio signals and transmit them to automatic listening stations (ALS).

Tracking salmonids between the sea and freshwater

CART (combined acoustic and radio) tags, which can switch from acoustic to radio transmission after a pre-set time interval (Solomon and Potter 1988), or in direct response to a change in salinity (Dearey *et al.* 1998; Niezgoda *et al.* 1998) are used to track adult fish through estuaries. CEFAS CART tags, which

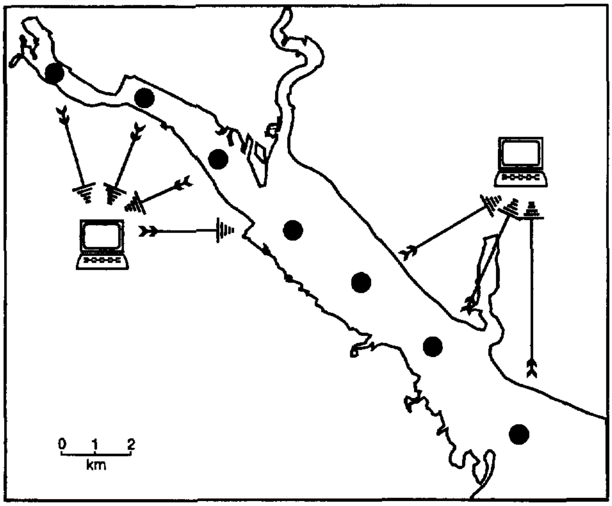

Figure 3. Chart of Southampton Water indicating the positions of acoustic sonar buoys (●) and automatic listening and data logging stations (🖳) (Moore *et al.* 1998).

incorporate a 76 kHz acoustic transmitter and a 173.7-174.0 MHz radio transmitter, are 70 mm long by 16.5 mm in diameter and weigh 4.5 g in water. The tags are individually identified by radio frequency and pulse rate, and switch from acoustic to radio transmission at a pre-set time. They can be detected at ranges up to 300 m, depending on water conditions.

It became possible to study the downstream movements of juvenile Atlantic salmon (*Salmo salar*) and sea trout (*S. trutta*) in the early 1990s, with the development of an acoustic pinger small enough to be attached to wild smolts (Moore *et al.* 1990a). This miniature tag (17 mm long, 8 mm dia.), which operates at a frequency of 300 kHz and has a life of about 35 days, weighs 1.3 g in air and 0.35 g in water. Pulse repetition rate, which is used to identify individual fish, can be set between 40-120 pulses per minute. The acoustic source level of the tag is 148 dB re 1μPa at 1 m ± 3 dB. The maximum range of detection varies with the acoustic properties of the water. In a fast-flowing estuary with a high sediment load, for example, the range may be only about 75 m; in the open sea ranges of up to 230 m are achievable (A. Moore, pers. comm.). Miniature pingers are surgically implanted in the peritoneal cavity of wild smolts trapped in freshwater during downstream migration. Smolt survival is not adversely affected by this method of tag attachment and a twelve month laboratory study (Moore *et al.* 1990b) indicated no significant effect on behaviour or physiology.

CART tags and miniature pingers are both used in conjunction with a chain of sonar buoys anchored at key positions along the estuary (Solomon and Potter 1988) and monitored with one or more automatic listening stations (Figure 3). Each ALS can monitor signals from up to five sonar buoys. Environmental data, such as temperature, salinity and water quality are monitored at stations close to the sonar buoys. The data logger on the ALS provides a record of the date and time at which each tag signal was detected, the identity of the buoy that detected it and an audio recording of the pulse rate of the tag, which allows the identity of the fish to be established.

Tracking juvenile salmonids in coastal waters

It has recently become possible to study the behaviour of smolts in near-shore coastal waters after emigration from the estuary (Moore 1996). Individual fish are tracked manually using a directional hydrophone on a small (~30 m) research launch, whose geographical position is fixed every 2 min using GPS. Smolts are tagged in freshwater and followed down the estuary with a chain of sonar buoys, as described above. The launch is anchored alongside the most seaward sonar buoy until the tag signal is detected by the hydrophone on the buoy. The launch then recovers its anchor and follows the fish, keeping the tag signal within detectable range (100-150 m). The hydrophone can be operated in vertical mode to give an indication of whether the smolt is swimming close to the surface or close to the bottom.

Tracking salmonids in relation to estuarine barrages

There is considerable concern in the UK about possible adverse effects of barrages on estuarine fish ecology. These barrages, which have been constructed for amenity value or power generation, modify the tidal regime and have the potential to disrupt the migrations of diadromous species, which migrate between sea and freshwater at different stages of their life histories. Fine-scale movements of migrating salmonids can be observed with the CEFAS HiRes system (Russell *et al.* 1990; Kell *et al.* 1994), which depends on the detection of a signal from a 76, or 300 kHz acoustic tag by at least three hydrophones placed at known co-ordinates in the study area. A timer gate interface linked to a PC is used to measure the interval between the time of arrival of the tag signal at each buoy of a pair. The position of the tag is estimated by a non-linear least squares technique. The system can be used with miniature 300 kHz acoustic pingers to record the behaviour of salmonid smolts migrating downstream past the barrage or with 76 kHZ CART tags to follow upstream passage of adult fish (Russell *et al.* 1998).

Discussion

The application of acoustic tracking technology to fisheries research has resulted in some important advances in our understanding of how fish react to their environment and how behaviour affects the efficiency of fishing gear. It has also led to new discoveries about mechanisms of migration and patterns of movement that are leading to a better understanding of stock structure and distribution. Short tag life and the inability to follow more than one fish at a time have, however, both been major limitations. Although tracking will still be needed for some years yet to make detailed observations, or address specific physical or physiological questions, the general trend of future development is likely to be increasingly toward systems that allow observations to be replicated with many fish at the same time. These systems are likely to involve archival (data storage) tags, pop-up tags that release from the fish at pre-set times and transmit data to the laboratory by radio or satellite, and coded acoustic tags that can be used in conjunction with automatic listening stations. Improved systems of acoustic telemetry may also allow data to be recovered in some circumstances, without the need to recapture the fish and remove the tag. It should also become feasible to build smaller acoustic tags as electronic components get smaller or custom-built integrated circuits become affordable. Tags may, however, not necessarily get much smaller in the foreseeable future. The size of batteries is likely to remain a limiting factor for some years and it may be desirable to utilise some of the space saved by incorporating several different sensors. Physiological telemetry is, as yet, in its infancy and major developments in this field are to be expected in the next few decades, along with further advances in understanding of fish behaviour.

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