

An autonomous free-fall acoustic tracking system for investigation of fish behaviour at abyssal depths

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Abstract

The Code Activated Transponder (CAT) ingestible fish tag capable of operating at depths of 6000 m is described. The CAT is acoustically interrogated by a scanning sonar mounted on the AUDOS free-fall camera lander vehicle. The CAT, 12.5 mm diameter and 65 mm long works at ultrasonic frequencies (77 kHz) and can be tracked to a range of 500 m. The AUDOS lander incorporates the new TRATEX (Transponding Acoustic Tracking Experiment) system that logs direction and range of individually tagged fish together with current and compass information. Typical results are shown from a track of 3 *Coryphaenoides(Nematonurus) armatus* (Macrouridae) taken at the Porcupine Seabight in the North Atlantic (49° 35' N-13° 43' W), 3500 m deep. The mean fish swimming speed was 0.087 m.s⁻¹. Despite their low speed, fish moved independently of the bottom current, either cross-current or against the current, optimising the chance of encountering odour plumes from new food falls.

Keywords: Deep sea, acoustic tags, transponder, fish, tracking, *Coryphaenoides*, Macrouridae, sonar.

Un système acoustique pour l'observation du comportement des poissons abyssaux.

Résumé

Il s'agit de la description d'un système de marque acoustique interrogeable par ultrasons (CAT) « pouvant être ingérée » par des poissons. Ce système est capable d'opérer à des profondeurs de 6000 m. Le CAT est interrogeable de façon acoustique au moyen d'un sonar à balayage monté sur un véhicule et comportant un appareil photo AUDOS. Le CAT a un diamètre de 12,5 mm et 65 mm de long, fonctionne par ultrasons (77 kHz) et peut être suivi sur 500 m. Le véhicule AUDOS comprend le nouveau système TRATEX (expérience de suivi par acoustique) qui indique la direction et le parcours du poisson marqué individuellement ainsi que les courants et sa position. Les résultats caractéristiques sont montrés à partir du suivi de 3 *Coryphaenoides (Nematonurus) armatus* (Macrouridae) pris sur les fonds de Porcupine en Atlantique Nord (49° 35'-N 13° 43' W) à 3500 m de profondeur. La vitesse moyenne de nage du poisson est de 0,087 m.s⁻¹. En dépit de cette vitesse assez lente, les poissons nagent indépendamment du courant de fond, soit au travers du courant, soit contre le courant, optimisant leur chance de rencontrer des zones d'odeurs en provenance de nouvelles chutes de nourriture.

Mots-clés : Grands fonds, marque acoustique, poisson *Coryphaenoides*, Macrouridae, sonar.

INTRODUCTION

Baited camera systems have been used for many years to observe deep-sea demersal fish *in situ* (e.g. Isaacs, 1969 and Isaacs and Schwartzlose, 1975; Smith *et al.*, 1979; Wilson and Smith, 1984). Priede and Smith (1986) showed that abyssal grenadier fishes, *Coryphaenoides (Nematonurus) armatus* and *Coryphaenoides (Nematonurus) yaquinae*, would ingest acoustic pingers embedded in the bait deployed within view of the camera. The pingers are retained in the stomach for at least 26 h (Armstrong and Baldwin, 1990) and experiments on shallow water species indicate much longer retention times without disturbing normal feeding behaviour (Armstrong *et al.*, 1992). Using these acoustic stomach tags, the movements of *C. (N.) armatus* and *C.(N.) yaquinae* have been studied at different localities in the North Atlantic and Pacific Oceans (Priede *et al.*, 1990, 1991; Armstrong *et al.*, 1991; 1992b). The rate of fish dispersal from the bait source was estimated using signal attenuation as a measure of distance from a calibrated hydrophone attached to the camera vehicle. This method is not very precise (Bagley *et al.*, 1990) but by averaging over a large number of readings mean radial velocity was estimated as 0.11 m.s^{-1} . This is of the same order of magnitude as the bottom tidal current and the question arises as to whether grenadiers drift with the current to save energy as of some shallow-water fishes (Metcalf *et al.*, 1990), or do they move across or against the current in an optimal search pattern (Dusenberry, 1989). Some useful information has been gained by use of a scanning directional hydrophone (Priede *et al.*, 1991; Armstrong *et al.*, 1992) to measure bearing but a method is required that can unambiguously provide instantaneous locations of individual fish within a two dimensional co-ordinate system. Fish equipped with pingers can be tracked by measurement of time of arrival of signals within a multiple hydrophone array (Hawkins *et al.*, 1974; Urquhart and Smith, 1992). Precision deployment of such an array at abyssal depths would be difficult. We have adopted an alternative approach using instruments on board the camera platform to measure location in a polar co-ordinate system referenced either to compass direction or current flow direction.

The code activated transponder (CAT) (Bagley, 1992) is comparable in size to the original pingers used by Priede *et al.* (1990) and is readily ingested by deep-sea grenadiers. The transponder principle has been used previously by Mitson and Storeton-West (1971), to track plaice (*Pleuronectes platessa*) in the North sea. Their transponder, attached to the fish externally, was triggered by acoustic pulses from a ship-borne sonar. The transponder response appeared as a bright dot on the sonar display indicating the range and bearing of the fish relative to the vessel against the background of echoes from the bottom and other features in the water. The CAT only responds if interrogated

with a predetermined code specific to an individual transponder. This system therefore, can track several individually distinguishable fish simultaneously and can also select a single fish ignoring other transponders within range of the system.

The distance between the surface and the abyssal ocean floor exceeds the range of any practical ship-borne high frequency sonar (Mitson, 1983) so the CAT system is used with an autonomous interrogation and data logging system. The system was developed as part of a study of the abyssal fauna in both the North Atlantic and North Pacific Oceans at depths ranging from 750 m to 4 100 m. The regions investigated have a rich benthic community and mobile grenadier fish may play a significant role in transport of organic carbon.

MATERIALS AND METHODS

The Code Activated Transponder

The transponder is activated by a dual pulse code transmitted by the interrogating sonar. The activation code consists of two 10 ms acoustic pulses, separated by a programmable time period (Fig. 1). The arrival of the first acoustic pulse "wakes up" all CAT tags within range. Each CAT then waits for a unique pre-programmed period of time before expecting a second 10 ms acoustic pulse. If this second acoustic pulse falls within the expected time window the transmitter is activated and a return pulse is sent to the interrogating sonar. Should the second pulse not appear during the expected window, the CAT will return to a "sleep" state without activating the transmitter.

Figure 2 shows the basic operational diagram of the CAT. A common transducer is used for both the receiver and transmitter. The parallel combination of the transducer capacitance and the output transformer inductance forms a 77 kHz tuned circuit that helps to reject spurious signals. The transducer is capacitively coupled into the receiver and the signal is amplified

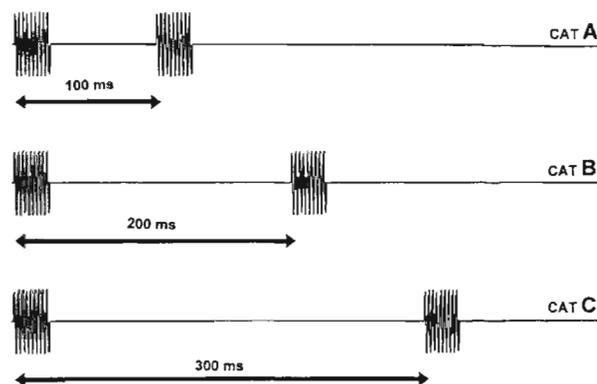


Figure 1. – Typical interrogation codes for three code-activated transponders deployed simultaneously.

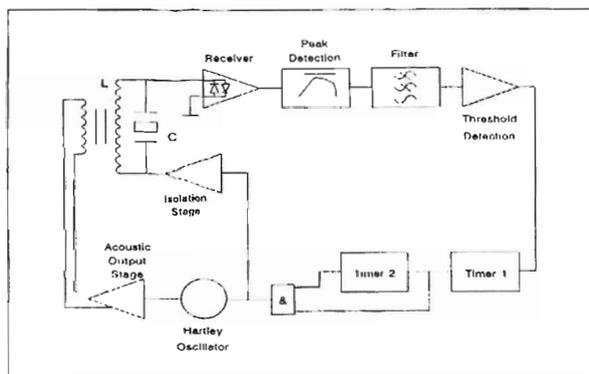
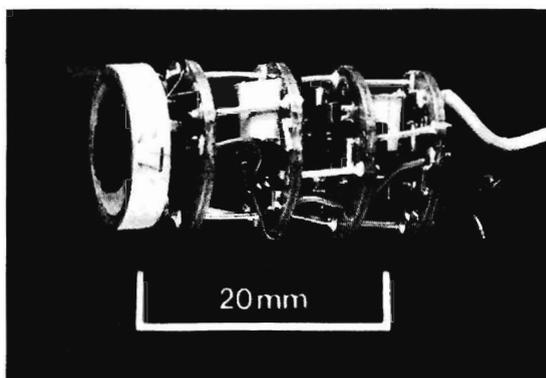


Figure 2. - Code-activated transponder functional diagram.

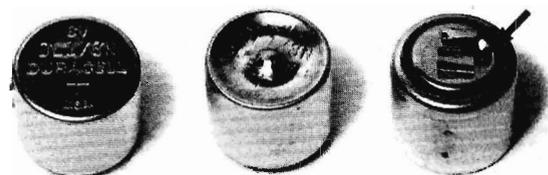
by a three stage transistor amplifier with a gain of 87 dB. The receiver output is wave shaped by a peak detector and filtered to produce a suitable input to the digital detection stage. A threshold detection circuit maintains a level below which any receiver input will be ignored, thereby preventing background noise falsely triggering the following digital stage. Due to limited space available, the CAT receiver is very basic and therefore distortion occurs due to high gain and the use of limited DC biasing. For our application this effect does not present a real problem as only the envelope of the input acoustic pulse is required by the digital detection stage.

Timers 1 and 2 are one-shot monostables. When triggered by a receiver output voltage that is above the detection threshold level, these timers will ignore any further inputs until the end of their timing sequence. Due to the serial connection of these timers, timer 1 triggers on the first pulse of an acoustic interrogation code, and timer 2 triggers on the completion of the timing sequence of timer 1. The second acoustic pulse, therefore must occur after the timing sequence of timer 1, but before the end of the timing sequence of timer 2 to enable the next stage. When this occurs, the Hartley oscillator generates a 77 kHz waveform that drives the high power (167 dB ref. 1 μ Pa at 1 m) output stage, otherwise the oscillator is not enabled and the CAT returns to a "sleep" state. The return pulse duration is determined by the time interval from reception of the second interrogation pulse to the end of the activation period of timer 2. Varying the value of timing elements of timer 2 therefore can be used to adjust the return pulse length. This can further aid recognition of the individual transponders triggered by the same code interval. The activation code of each CAT is pre-programmed by selection of timing components during assembly.

The CAT is designed to withstand hydrostatic pressures up to 600 atmospheres. Solid state surface mount electronic components are used which, due to their small volume and lack of voids, are able to withstand such pressures. The circuit is constructed on four 13 m diameter circular printed circuit boards. After testing, the circuits are built



(a)



(b)

Figure 3. - Code Activated Transponder (CAT) components. (a) Assembled circuit comprising 4 circular boards. The PZT ceramic ring at the left generates the 77 kHz acoustic signal. (b) Batteries. The CAT is powered by 2 lithium DL1/3N cells. The effect of pressure on these cells at abyssal depths is shown. Left - Standard cell prior to deployment. Centre - Standard Cell after retrieval, Note deformation under pressure, and the central bulge where the cathode contacts the casing and creates a short circuit. Right - Hole drilled in the casing (arrowed) to allow pressure compensation and correct operation at depth.

into a stack configuration (Fig. 3a) and inserted into a polypropylene test tube 13 mm internal diameter and 65 mm long. The transducer is a lead zirconate titanate ceramic cylinder (12.5 mm diameter) which is resonant in the hoop mode at a frequency of 77 kHz. The resonant frequency of the transducer depends on transducer diameter and this is an important factor determining the physical dimensions of the CAT.

The circuit and battery are inserted into a silicon oil filled tube and sealed with a rubber bung. The oil acts as a pressure compensating fluid and provides acoustic coupling between the transducer and the sea water. A 6 volt lithium manganese battery is used (Duracell type PX28L), comprising two DL1/3N 3V cells. These have an air space inside and when subjected to pressure the casing distorts creating a short circuit between the central cathode and the external casing (Fig. 3). A hole drilled in the top (negative end) of each cell, permits infusion of inert silicon oil to compensate for compression and thus

prevents collapse. (This operation is not recommended by the battery manufacturer, and the user must be aware of the potentially explosive nature of lithium cells).

The Aberdeen University Deep Ocean Submersible (AUDOS)

The transponder interrogator system is mounted on a conventional free-fall camera vehicle similar to those described by Wilson and Smith (1984), Laver *et al.*

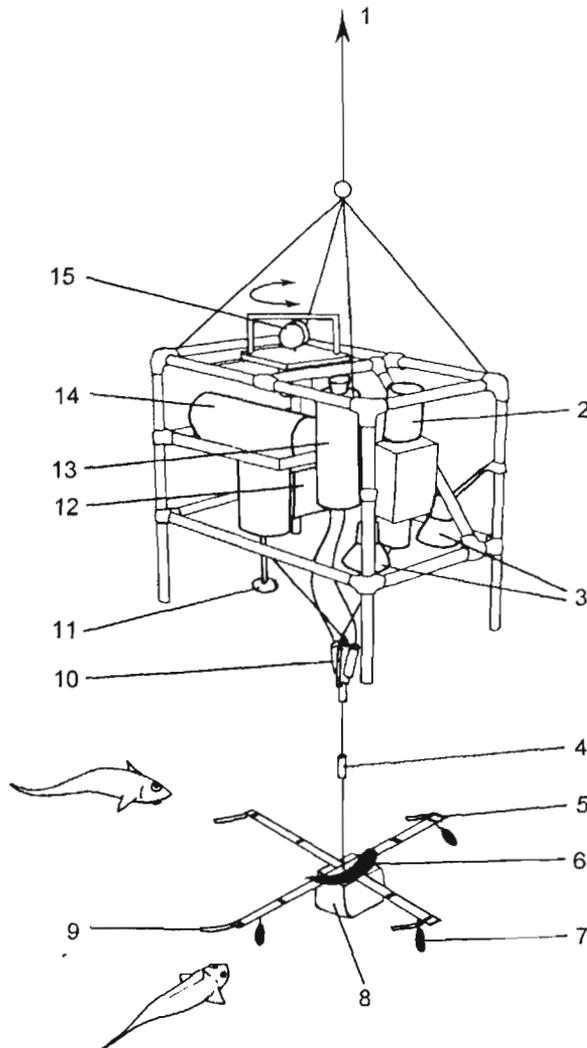


Figure 4. – The AUDOS free-fall lander vehicle incorporating all the instruments required for TRATEX controlled deep-sea fish tracking. For clarity some structural members and cables on the main chassis are omitted. 1. Line to buoyancy spheres, 2. Film camera, 3. Camera flash heads, 4. Soluble magnesium link (back-up ballast release), 5. Scale cross, 6. Main bait, mackerel, 7. Bait parcel containing Code Activated Transponder (CAT, Acoustic 77 kHz), 8. Ballast, 9. Ribbon tell-tale current indicator, 10. Main ballast release mechanism, 11. Electromagnetic current meter probe, 12. Main Battery, 13. Acoustic release command unit (10 kHz link to surface), 14. TRATEX housing, 15. Sonar scanning head.

(1985) and Priede *et al.* (1990). A tubular frame (HE30 aluminium alloy) constructed using galvanised clamps (Kee clamps) supports and protects the instrument housings (Fig. 4). Buoyancy is provided by 44 cm diameter glass spheres (Benthos Inc.) in the mooring above the vehicle which is terminated by a mast assembly with a radio beacon (Novatech Ltd.), strobe light (Novatech Ltd.) and large flag to aid recovery from a surface ship or by a time release. A Mg/Fe corrodible link is used as back-up in case of failure of the electronic releases. The length of wire between the vehicle frame and the ballast determines the height of the sea floor and hence the field of view of the downward looking camera.

The vehicle frame supports a camera, flash unit, twin 200 J flash lights (C1800 system, Camera Alive, Aberdeen, UK), two batteries, scanning directional transducer, electronic current meter, compass and the experiment controller known as TRATEX (Transponding Acoustic Tracking Experiment).

The operation of TRATEX is illustrated in the block diagram of Figure 5. The TRATEX system uses a 6301 based microcontroller (Onset Computer Corporation). A control program is loaded via an RS232 link from a host P.C. Loaded programs are retained after the power is removed and are immediately restarted when power is re-applied. The micro-controller has an on-board 8-channel 12 bit-analogue to digital converter, and a 16 bit digital input/output interface. The 8 analogue channels are used to interface to the 8-channel TRATEX analogue bus, with the 16 bit digital input/output interface used for data transfer and "handshaking" purposes. A battery backed 512 kbyte memory element (Datafile) stores all the data gained during an AUDOS deployment. This is off-loaded via the RS 232 link to the host P.C. when the vehicle is recovered.

All the instruments used by the TRATEX system operate via an instrument interface which is connected to the system backplane. The backplane contains busses, address lines, handshaking signals, and the available power connections. An interface operates by remaining in a low power "sleep" state until it is addressed and instructed by the microcontroller. The interface is then able to operate in the background gathering the information required for its instrument, allowing the microcontroller to complete other tasks if required.

The present configuration has 6 instruments in use, 3 internal to the TRATEX pressure housing and 3 external. The internal instruments include the power supply, compass and Digital Audio Tape (DAT). The external instruments are the electromagnetic current meter, camera and flash unit and the transducer scanning unit.

The power supply uses an external 12V 36 Ah deep-sea battery (Aberdeen University design) as its input. This provides all the TRATEX and instrument supplies, apart from the camera and flash which are

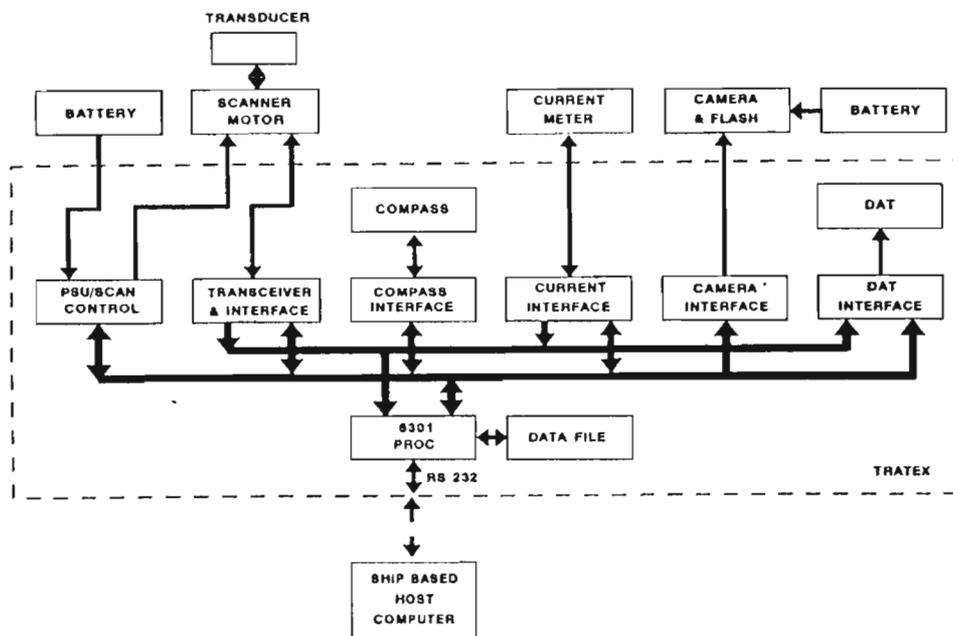


Figure 5. – Transponding Acoustic Tracking Experiment (TRATEX) functional diagram.

powered separately. A further 3 auxiliary supplies are under software control. The first is for high current instruments that are only powered up for short periods, such as the current meter and compass. The 2 remaining auxiliary supplies are of opposed polarity and are switched to the DC scanner motor to provide clockwise and anti-clockwise rotation.

An on-board internal electromagnetic compass (Cetrek Ltd.) is powered at the start of each scanning sequence and produces a stream of digital pulses, the number of which represents vehicle orientation. The compass interface converts this data into an 8 bit byte which is stored in an on-board buffer. When requested, the interface transmits the data via the TRATEX digital bus to the microcontroller for permanent storage in the datafile.

An external two axis electromagnetic current meter (Valeport Marine Scientific Ltd.) measures the magnitude and direction of the local ocean current relative to the AUDOS frame. (The true direction is calculated off-line on the host P.C. using compass and current meter data files). The current meter output comprises two dual polarity voltages representing the rectangular co-ordinates of the current magnitude and direction vector at the sensor head. The sensor is an 11 cm diameter disc design which minimises measurement errors in the typical abyssal plain current environment (Griffiths *et al.*, 1978). The outputs are pre-scaled and filtered by the current meter interface before direct connection to the microcontroller analogue to digital converter. The resulting 12-bit data word is stored in the datafile for off-loading on recovery.

A Digital Audio Tape (Casio DA-1) is used in a back-up capacity to periodically record acoustic data. This aids fault detection and was particularly important during software development. Three control lines, stop, play and record are operated from the DAT interface.

An 800 frame capacity 35 mm film camera and flash unit (Camera live Ltd., CI800) is used to photograph fish attracted to the bait (Armstrong *et al.*, 1992). TRATEX controls the operation of the camera via two available trigger lines that override the internal intervalometer. We have used Ektachrome colour transparency film, segments of which can be developed on board ship to check system function.

The scanning unit shown in Figure 6, rotates the directional transducer (-3dB beam width 15.8°) through 360° . The unit consists of a DC motor and gearbox, rotation potentiometer and switch all immersed in Fluorinert Electronic fluid (Type FC77, 3M Industrial Chemical Products Division) in a pressure-compensated acrylic plastics housing. The motor drives a shaft which passes through an "O" ring seal beneath the hydrophone mount. The direction and duration of rotation are controlled from the TRATEX unit. The rotation potentiometer acts as a feedback element that monitors angle of rotation. The motor is stopped 52 times during a full 360° rotation to interrogate each CAT. Once the transducer is fully rotated, the TRATEX system terminates the scanning sequence and returns to a low-power "sleep" state. During the next scanning sequence the rotation direction is reversed to prevent damage to the transducer cable. Rotation greater than 360° is prevented by the use of two back-up systems. The first

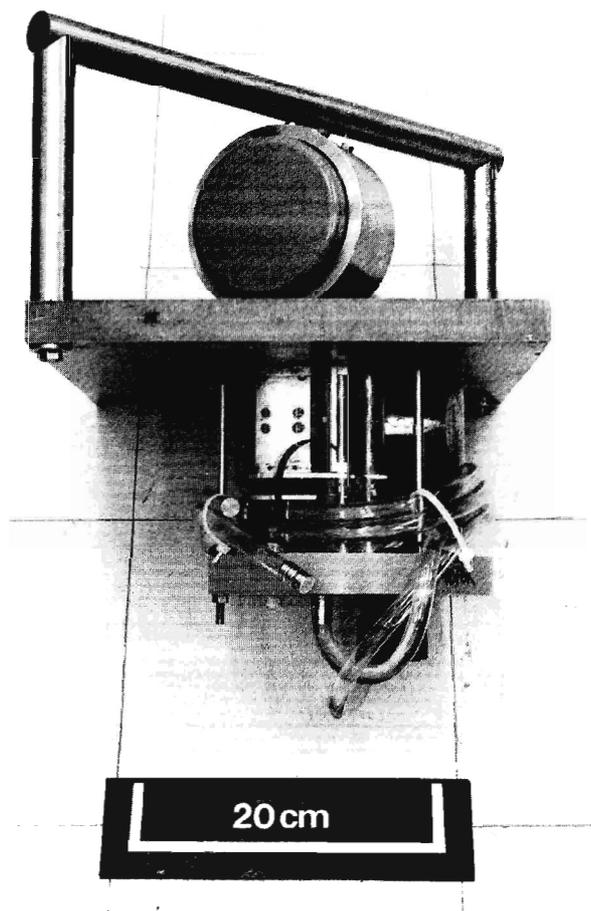


Figure 6. – The AUDOS scanning transducer unit. The motor and gear box are in the transparent fluid-filled housing below which is pressure compensated by the flexible fluid-filled tubes. A vertical shaft rotates to the transducer above via an “O” ring seal.

is a mechanical limit switch that generates a software interrupt into the TRATEX control program and the second is provided by a software time-out function that stops the motor before the system jams.

Transceiver

The transceiver transmits and receives through a single Lead Zirconate Titanate ceramic disc transducer which is 75 mm in diameter and resonant in the thickness mode at 77 kHz. The transducer is immersed in silicon oil and is backed by a disc cast from polyester resin loaded with glass microballoon spheres (Emerson and Cuming Inc. Eccospheres P8) ensuring directional sensitivity.

The transceiver, although connected to both the digital and analogue buses also has a direct “high speed” link to the microcontroller. The timings for the acoustic activation codes are software controlled. A logic level input to the transceiver triggers a 77 kHz

since wave that drives the transducer through a push-pull output stage at 197 dB re $1\mu\text{Pa}$ @ 1m acoustic output (Directivity index = 20 dB).

The transducer is coupled to the receiver using an impedance matching transformer and capacitive coupling stage. A pre-amplifier in the transducer head is followed by an 87 dB amplifier within the TRATEX system. In-band signals are filtered and converted to a voltage which is proportional to the power of the acoustic input signal. This voltage is fed to a comparator producing a logic level output if the signal is above reference. The comparator reference is time variable, and ramps downwards after each interrogation pulse. The period between interrogation and return signal is timed by the TRATEX software and stored in the datafile for conversion to a range measurement on the host PC. Range was calculated assuming velocity of sound to be $1\,534\text{ m.s}^{-1}$ derived from standard equations (Bagley, 1992).

Experimental protocol

Fish were attracted to AUDOS by mackerel (*Scomber scombrus*) bait standardised as approximately 0.5 kg to allow comparison of data between studies. Flesh from the mackerel was ground up and used to fill a nylon mesh boat bag into which the CAT was inserted. The rest of the fish, was tied to the middle of the cruciform scale. The CAT bait bags were attached by cotton threads about 5 cm long so that the baits were no more than 30 cm above the sea floor. Three CAT tags were deployed at a time, each with different activation code; 100, 200 and 300 ms nominal pulse intervals.

The AUDOS software enables the system sampling rates to be altered depending on the expected response time of the deep-sea fauna of interest. A typical operational sampling rate for a eutrophic area, where scavenging fish respond rapidly to bait falls would be to take a photograph every minute and to initiate a scanning sequence every 10 minutes. In more oligotrophic areas where fish respond more slowly, longer time intervals between samples can be used, possibly tapering with increasing durations between samples as the experiment progresses. The samples can be distributed optimally throughout the planned time course of the experiment making full use of the available film and memory capacity.

RESULTS

Figure 7 illustrates a typical set of CAT tracks during an AUDOS deployment. The data were obtained at a sounding of 3 500 m on the continental rise in the area of the Porcupine Seabight, North East Atlantic Ocean ($49^{\circ}35.18'N-13^{\circ}42.66'W$). (Bagley *et al.*, 1994). Only one species of fish was attracted to the bait, the grenadier *Coryphaenoides (Nematonurus) armatus* at the optimum depth for this species (Priede

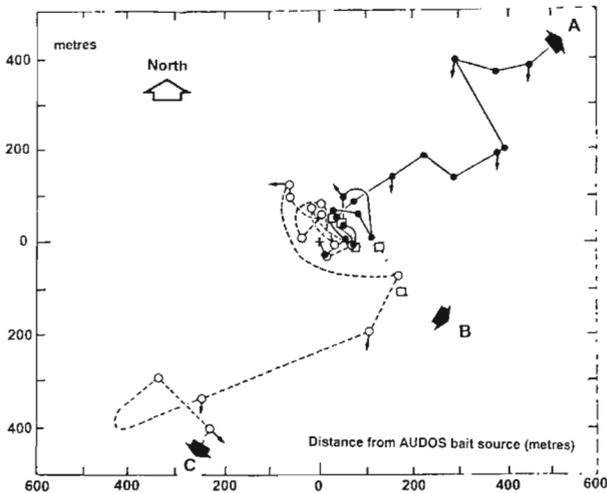


Figure 7. – Tracks of three fish, *Coryphaenoides (Nematonurus) armatus* tracked simultaneously at a depth of 3500 m in the NE Atlantic Ocean. The AUDOS position where the bait with CATs was deployed is in the centre of the figure. The small arrows indicate current direction as detected at the AUDOS at the time of the location. Arrows are omitted to avoid over-crowding the figure. The large arrows indicate the presumed final radial departure direction.

et al., 1994b). The first fish arrived 16 min after the bait reached the sea floor and by 44 min, 10 fish were present. Three of these fish ingested CATs. Initially the current was setting towards the north west and the fish all circulated around within 100 m of the bait source. Once the bait was exhausted all three fish began to move away. Contact was lost with fish B at a range of 210 m as it moved south eastwards against the current. Fish A and C departed in opposite directions and were tracked moving away across current at the 500 m maximum range of the tracking system. The three fish were clearly moving independently of one another and independently of the current. The mean speed of these three fish over the bottom was 0.08 m.s^{-1} and they departed from the area covered by the tracking system within 10 hours after the initial AUDOS touchdown time.

DISCUSSION

The CAT is a relatively complex device compared with pingers usually used in animal tracking studies (Priede, 1992). This study shows that such devices can now be built small enough to be ingested by fish and an experiment can be carried out on a several fish simultaneously using an autonomous lander vehicle. The surface ship is only required for initial deployment and recovery of the tracking system.

Immediate advantages over the previous pinger system are apparent. Using pingers it was not possible to distinguish between individual fish so all data were pooled to give population mean dispersal rates (Priede *et al.*, 1991). Using CATs it is possible to estimate individual fish swimming speeds.

Using pingers the estimated ranges of were ascribed to 200 m range bins (Priede *et al.*, 1990; Armstrong *et al.*, 1990). The range precision of the CAT system is 0.5 m. The range error using the pingers increased with range so that at maximum range (900-1 000 m) the true range uncertainty might be as much as 500 m. It was only by averaging large numbers of data points that estimates of speeds were obtained. The velocities in the present study are somewhat lower than the mean radial velocity of 0.11 m.s^{-1} estimated by (Priede *et al.*, 1991) The previous velocity measurements depended on assumptions regarding signal source levels and attenuation in the abyss that could not be independently verified. The CAT range estimates however are robust with little scope for error other than perturbations in the velocity of sound which varies by less than 1 %. The code serves to prevent spurious reverberations or noise which can be a problem with some transponder systems. The CAT system is clearly capable of measuring differences in swimming speed and will be a useful tool for future research investigating seasonal changes in the deep sea, (Priede *et al.*, 1994a; Smith *et al.*, in press).

The movements of the fish are across or against the current which we suggest optimises the chances of encountering odour plumes from new food falls. The *Coryphaenoides (N.) armatus* despite their low speeds are clearly not drifting with the current.

Acknowledgements

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REFERENCES

- Armstrong J. D., P. M. Bagley, I.G. Priede 1992. Photographic and acoustic tracking observations of the behaviour of the grenadier, *Coryphaenoides (Nematonurus) armatus*, the eel, *Synaphobranchus bathybius*, and other abyssal demersal fish in the North Atlantic Ocean. *Mar. Biol.* **112**, 535-544.
- Armstrong J. D., R. Baldwin 1990. A method for testing retention of transmitters swallowed by deep-sea fish. *J. Fish Biol.* **36**, 273-274.
- Armstrong J. D., P. M. Bagley, I. G. Priede 1992. Tracking deep-sea fish using ingestible transmitters and an autonomous sea-floor instrument package. In: *Wildlife Telemetry: Remote monitoring and tracking of animals*. I. G. Priede S. M., Swift eds. Ellis Horwood, Chichester, 376-386.
- Armstrong J. D., A. D. F. Johnstone, M. C. Lucas 1992b. Retention of intragastric transmitters after voluntary ingestion by captive cod, *Gadus morhua* L. *J. Fish Biol.* **40**, 135-137.
- Bagley P. M. 1992. A code-activated transponder for the individual identification and tracking of deep-sea fish. In: *Wildlife Telemetry: Remote monitoring and tracking of animals*. I. G. Priede, S. M. Swift eds. Ellis Horwood, Chichester, 111-119.
- Bagley P., I. G. Priede, J. D. Armstrong 1990. An autonomous deep ocean vehicle for acoustic tracking of bottom living fishes. In: *Monitoring the Sea*, Digest No. 182: Ref. E15/E11. Institute of Electrical Engineers, London, 2/1-3.
- Bagley P. M., A. Smith, I. G. Priede 1994. Tracking movements of deep demersal fishes, *Coryphaenoides (Nematonurus) armatus*, *Antimora rostrata* and *Centroscymnus coelolepis* in the Porcupine Seabight, N.E. Atlantic Ocean. *J. Mar. Biol. Assoc. UK.* **74**, 473-480.
- Dusenberry D. B. 1989. Optimal search direction for an animal flying or swimming in a wind or current. *J. Chem. Ecol.* **15**, 2511-2519.
- Griffiths G., P. G. Collar, A. C. Braithwaite 1978. Some characteristics of electromagnetic current sensors in laminar flow conditions. Institute of Oceanographic Sciences, Rep. 56, Surrey, England.
- Hawkins A. D., D. N. MacLennan, G. G. Urquhart, C. C. Robb 1974. Tracking cod *Gadus morhua* L. in a Scottish Sea Loch. *J. Fish Biol.* **6**, 225-236.
- Isaacs J. D. 1969. The nature of oceanic life. *Sci. Am.* **175**, 636-637.
- Isaacs J. D., R. A. Schwartzlose 1975. Active animals of the deep-sea floor. *Sci. Am.* **233**, 84-91.
- Laver M. B., M. S. Olson, J. L. Edelman, K. L. Smith Jr. 1985. Swimming rates of scavenging deep-sea amphipods recorded with a free vehicle video camera. *Deep-Sea Res.* **32**, 1135-1142.
- Metcalfe J. D., G. P. Arnold, P. W. Webb 1990. The energetics of selective tidal stream transport: an analysis of plaice in the Southern North Sea. *J. Mar. Biol. Assoc. UK.* **70**, 149-162.
- Mitson R.B. 1983. Fisheries sonar. Fishing News Books, Farnham, England, 210 p.
- Mitson R. B., T. J. Storeton-West 1971. A transponding fish tag. *Radio Electron. Engineer.* **41**, 438-489.
- Priede I. G. 1992. Wildlife telemetry: an introduction. In: *Wildlife Telemetry: Remote monitoring and tracking of animals*. I. G. Priede, S. M. Swift eds. Ellis Horwood, Chichester, 3-25.
- Priede I. G., K. L. Smith Jr. 1986. Behaviour of the abyssal grenadier, *Coryphaenoides yaquinae*, monitored using ingestible acoustic transmitters in the Pacific Ocean. *J. Fish Biol.* **29** (Suppl. A), 199-206.
- Priede I. G., K. L. Smith Jr., J. D. Armstrong 1990. Foraging behaviour of abyssal grenadier fish: inferences from acoustic tagging and tracking in the North Pacific Ocean. *Deep-Sea Res.* **37**, 81-101.
- Priede I. G., P. M. Bagley, K. L. Smith Jr. 1994a. Seasonal change in activity of abyssal demersal scavenging grenadiers *Coryphaenoides (Nematonurus) armatus* in the eastern North Pacific Ocean. *Limnol. Oceanogr.* **39**, 279-285.
- Priede I. G., P. M. Bagley, A. Smith, S. Creasey, N.R. Merrett 1994b. Scavenging deep demersal fishes of the Porcupine Seabight, (NE Atlantic Ocean); observations by baited camera, trap and trawl. *J. Mar. Biol. Assoc. UK.* **74**, 481-498.
- Smith A., I. G. Priede, P. M. Bagley, S. W. Addison 1997. Interception and dispersal of artificial food falls by scavenging fishes in the abyssal NE Atlantic: early season observations prior to annual deposition of phytodetritus. *Mar. Biol.* (In press).
- Smith Jr. K. L., G. A. White, M. B. Laver, R. R. McConnaughey, J. P. Meador 1979. Free vehicle capture of abyssopelagic animals. *Deep-Sea Res.* **26**, 57-64.
- Urquhart G. G., G. W. Smith 1992. Recent developments of a fixed hydrophone array system for monitoring movements of aquatic animals. In: *Wildlife Telemetry: Remote monitoring and tracking of animals*. I. G. Priede, S. M. Swift eds. Ellis Horwood, Chichester, 342-353.
- Wilson Jr. R. R., K. L. Smith Jr. 1984. Effects of near bottom currents on detection of bait by the abyssal fishes *Coryphaenoides* spp., recorded *in situ* with a video camera on a free vehicle. *Mar. Biol.* **84**, 83-91.