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An experimental technique for tracking dolphins in the vicinity of a trawl net

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Abstract
The system described in this paper provides a means of tracking one or more echolocating cetaceans (dolphins, porpoises and whales) in three-dimensional space. The aim of the research is to enable the behaviour of cetaceans to be observed passively in the wild in the vicinity of a large trawl net and to evaluate the effectiveness of deterrents intended to prevent the by-catch of these animals.

1. Introduction
The purpose of the tracking system described here is to monitor the precise underwater movements of echolocating cetaceans, notably in the vicinity of a large trawl net. The aim of the research is to provide information that may lead to a reduction in the by-catch of these animals [1,2]. For example, by observing a dolphin as it approaches the net it may be possible to determine if or at what range it becomes aware of the danger and takes evasive action. By observing the reactions of an approaching animal to various deterrents, such as sonar reflectors, active sources or predator recordings, the system may be used to choose the most effective warning system. Although the technique is applicable to any species of echolocating cetacean, most of the research carried out has been with the bottlenose dolphin (*Tursiops truncatus*).

The basis of the tracking technique is to use a widely-spaced array of hydrophones to receive the echolocation clicks produced by a dolphin in the vicinity of the net. To track a dolphin in three-dimensional space relative to some arbitrary datum point on the net, the clicks must be received by four hydrophones. Since the distance between the dolphin and each hydrophone is generally different, the spherically spreading acoustic wave generated by a click reaches the hydrophones (H1...H4) at different times, as indicated in Fig. 1. The arrival times (t1...t4) of the clicks are measured by a computer, either on-board the fishing vessel in real time or ashore during subsequent analysis. This is programmed with a novel tracking algorithm to calculate and display the instantaneous position of the animal. The resulting (X,Y,Z) coordinates can be displayed in the form of tracks on a computer screen or on a printer. The underwater units comprise pulse capture circuits for detecting the clicks, timing circuits for measuring the arrival time differences and a multiplexer/transmitter, the surface electronics comprise a receiver/demultiplexer, a desk-top computer and a suitable display, as shown in Fig. 2.

2. Deployment
Since the system is intended to track dolphins in the vicinity of a trawl net it is necessary to place the hydrophones so that their positions remains fixed relative to the net and to each
other. Two arrangements were initially considered, either locating the hydrophones on the net itself, or towing a remotely operated vehicle (ROV) with the hydrophones attached to it. At first, the use of the ROV appeared ideal because it had the advantage that the vehicle could be steered into any position in front of, beside or inside the net, and a camera on board the vehicle could confirm visually whether there are dolphins present and whether the tracking system is stable. Also, the ability to deploy the ROV, with the array attached, completely separately from the net would reduce the risk of damaging the underwater system by the net hauling gear.

A further advantage of the ROV was that it had a fibre optic transmission link capable of the high data rates necessary for this application (see later) but during a sea trial it was found that the noise generated by the ROV’s motors was too high for clear detection of the dolphin clicks. So the only solution available for future operation is to attach the hydrophones to the net, provided they are not all placed in the same plane and that no three are in line. The trial revealed that the net, measuring about 100m across and 50m high at the mouth, and some 400m long, remained remarkably stable as it was towed through the water at constant speed.

3. Transmission
In addition to ensuring that the hydrophone array is stable, a suitable method of transmitting the timing data back to the vessel had to be considered. The problem is complicated by the use of a high data rate (approximately 1.2Mbit/s) combined with a long transmission path (up to 500m).

In previous tracking trials in two-dimensional space, a multi-core cable was used as the transmission channel. Due to the increase in data rate required by the three-dimensional tracking system this cable no longer has sufficient capacity. An alternative channel is a cable of a higher specification, for example one with multiple twisted screened pairs, braided screen and a high insulation sheath suitable for use in sea water, together with the use of a suitable transmission protocol such as RS422. But the cable, line drivers and receivers would be used very close to the limit of their recommended data rates. This approach does not allow for any future increase in the throughput of the system, as may be required for error check codes, framing information and tracking several dolphins simultaneously, and it ignores the general rule of ‘over-engineering’ to produce a more robust system.

By using a fibre optic link to connect the underwater electronics to the fishing vessel, the system would be more versatile due to the wider channel bandwidth available. A typical fibre has a data rate of 10Mbit/s, which allows not only the digital timing information to be transmitted, but also the wide-band acoustic information received by the four hydrophones. This option would utilise about 10% of the channel capacity, ensuring that the transmission link would not limit any future expansion. For the purposes of sea trials, having the option to record the signals received by the hydrophones is a great advantage as it allows the data to be analysed off-line. Figs 3 and 4 illustrate the cable and fibre optic configurations respectively.

It can be seen that the decision to use one transmission medium rather than another is not immediately clear-cut. Due to the extremely harsh operating environment in which the
system must perform, a fibre optic link would require an armour-plated sheath and a second cable to provide power for the underwater electronics. With the abandonment of the idea of using a ROV for carrying the hydrophone array and for transmitting the timing data via the fibre optic links provided for its two TV cameras, the alternatives were to attach the hydrophones to the net and to design a modular system such that the transmission channel may be interchanged. If the system is used for the study of dolphins around a stationary net a conventional cable may be used to transmit the timing data to the surface. Alternatively, on a sea trial a fibre optic link could be used to transmit both digital timing data and the wide bandwidth acoustic information from the four hydrophones.

4. Tracking principles
To produce a valid estimate of a dolphin's instantaneous position, the tracking algorithm must determine the arrival times of the same click at the four hydrophones. It can be shown that the maximum spread of these arrival times is dependent only on the positioning of the hydrophones and the sound speed in water. Hence, the tracking process does not begin until one click arrival occurs unambiguously on each of the four channels in this time window, as shown in Fig. 5. The tracking algorithm then has to determine which click on channels two, three and four correspond to a given click on channel one. The clicks can, of course, arrive at the four hydrophones in any sequence; the problem is illustrated in Fig. 6. It can be shown that if a particular click's arrival times have been determined, then a time window can be calculated for each channel in which to search for the arrival of the next click. For example, if click \( n \) arrives first on channel 2, a search for the corresponding arrival on channel 1 is confined to the time window shown in Fig. 7. The width of the window \( \Delta t_0 \) is dependent on the maximum speed of the dolphin and the pulse repetition frequency \( (1/\Delta f_b) \). The positioning of the search window \( \Delta t_c \) can be determined by assuming that the position of the arrival on channel 1 relative to channel 2 does not change significantly between adjacent clicks. This assumption is valid for a comparatively slow moving acoustic source such as a dolphin.

In this way the arrival times for a particular click can be aligned and the time differences \( (\Delta t_{12}, \Delta t_{32}, \Delta t_{42}, \text{ etc.}) \) between channels can be calculated. These time differences are used as the input variables to a complex set of tracking equations [3]. It is assumed that the speed of sound in water is constant and that acoustic propagation occurs with negligible refraction and distortion. This algorithm produces two position estimates corresponding to the roots of a quadratic equation. One of these estimates is the true location of the dolphin, the other may be discounted by observing that the timing data corresponding to such a position does not match the times actually measured. A further test is performed to ensure that the estimated position is attainable by the dolphin, given its maximum possible velocity of about 10 m/s and its previously calculated position. If this is not the case then there remain two possibilities: either the new position is due to some inaccuracy within the system, or a new acoustic source has been detected. In the later case, the possibility of a second dolphin being present in the area is explored, thus producing two traces simultaneously.

The output of the tracking algorithm, i.e. the X,Y,Z coordinates, can be displayed in three dimensions with an (X,Y) plan view of the local area and a dive profile (Z, time), as shown in Fig. 8. To ensure that the system provides a realistic estimate of the path of a dolphin, the
tracking algorithm has to retain reasonable accuracy in the presence of any errors. In practice, the system is required to estimate positions to within a specified resolution, for example to better than 2m in the X, Y and Z co-ordinates in the region of interest. This specification determines the accuracy required by the electronic timing circuits and the minimum base-line length of the hydrophone array. Decreasing the base-line to make deployment easier dictates that the electronic timers must have a higher resolution, thus increasing the data rate on the transmission channel. It can be seen that a compromise must be made between these specifications.

6. Conclusions
A dolphin tracking system has been designed, based on the same principles adopted for tracking divers in earlier work. Computer simulations have been carried out to ensure that the programmed algorithm can acquire and track the position of a dolphin unambiguously. The main aspects of the system discussed here have been the practical problems of deployment and stability of the hydrophone array whilst being towed and the various methods of transmission from the hydrophone array to the towing vessel. Some of the problems have been addressed during a sea trial and further work is in hand to produce a real time system.

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References
Fig. 1 Radiation of a sound wave from a click

Fig. 2 - Block diagram of tracking system

Fig. 3 Transmission of timing data

Fig. 4 Transmission of timing data and acoustic information

Fig. 5 Acquisition of a dolphin's position

Fig. 6 Distribution of arrival times

Fig. 7 Click arrival time window

Fig. 8 Tracking display