Proceedings of the Institute of Acoustics

# PRINCIPLES OF TRACKING BIO-SONAR SOURCES UNDERWATER

B Woodward

Electronic and Electrical Engineering Department, Loughborough University, UK

## 1. INTRODUCTION

The advent of offshore exploration for oil and gas during the 1970s created a need for very accurate underwater position fixing for survey activities such as searching, mapping and photography, and for work tasks such as pipe laying, surface rig positioning, underwater structure positioning, towfish positioning, remotely operated vehicle navigation, subsea construction, mining, drilling and a vast range of other applications. The precision required dictates the use of underwater acoustic navigation and tracking techniques, and the best known of these employ arrays of hydrophones, beacons (also called pingers), transponders (receiver-transmitters) and responders (transmitter-receivers). For most of the tasks listed above the positioning is carried out only after a series of procedures to fix the position of the array on the sea bed; these may include transponder deployment, array baseline calibration and possibly absolute calibration in terms of geodetic co-ordinates by integrated satellite, surface and underwater data telemetry.

In this paper we consider how techniques and systems developed for industrial applications may be adapted for tracking echo-locating cetaceans (dolphins, porpoises and whales), in particular the principles of position fixing in three-dimensional space in real time. This is a problem that presents a serious engineering challenge. Details of the many position-fixing algorithms are not presented, because this information is available elsewhere, Milne [1], Cestone et al [2], Spindel [3], Hardman & Woodward [4], Musa et al [5], Morphett et al [6], Connelly et al [7].

## 2. CLASSIFICATION OF TECHNIQUES

Navigation at sea means finding the latitude and longitude of a surface vessel, i.e. in terms of co-ordinates in two-dimensional (2-D) space. Underwater navigation means finding the position a submarine, an autonomous underwater vehicle (AUV), a remotely operated vehicle (ROV) or a diver, i.e. in terms of co-ordinates in three-dimensional (3-D) space, which includes depth or altitude above the bottom. Tracking may be thought of as a form of navigation, e.g. an AUV or ROV tracked from a ship, or in the present context, echo-locating cetaceans tracked from the shore, Morphett et al [6], or from a boat, Connelly et al [7]. The modes of operation applicable to tracking cetaceans include (i) bearing/bearing, e.g. a boat with a directional hydrophone; (ii) range/bearing, e.g. a boat with a scanning sonar; and (iii) range/range, e.g. using an acoustic array, Milne [1].

In general, the types of systems used are classified by the length of the baselines of an array of hydrophones, beacons, transponders or responders, namely long baseline (LBL) for separations of greater than about 20m (and often as much as 5 km), short baseline (SBL) for separations of *typically* 5-20m, and super-short baseline (SSBL) for separations of less than about 0.5m. These figures do not represent hard and fast rules. The SBL and LBL techniques measure differences in arrival times of acoustic pulses from a source and are suitable for detecting a cetacean's echo-locations clicks, whereas the SSBL technique measures differences in phase of an acoustic signal. SBL and SSBL arrays can be attached to the hull of a boat, whereas a LBL array is sited on the sea bed. In all these configurations it is necessary to know the precise co-ordinates of the array.

## 3. SHORT BASELINE AND LONG BASELINE ARRAYS

A hull-mounted SBL array of hydrophones could be used to track one or more echo-locating cetaceans. Each click emitted is detected by three hydrophones $H_1$, $H_2$, $H_3$ at different times. The receiver measures the relative arrival times and, by assuming or measuring the sound velocity in the water, the three time differences are applied to an algorithm to calculate the position of the animal. Essentially, the co-ordinates of the cetacean are computed by finding the intersection of three spheres whose centres are at $H_1$, $H_2$ and $H_3$. Although only three hydrophones are considered here, in practice this would be a minimum number since some allowance for redundancy would normally be made and a fourth hydrophone is needed for three-dimensional tracking of this nature. In practical situations, corrections need to be applied for (i) the pitch and roll of the boat; (ii) the array centre offset from the boat's reference point; and (iii) translation of the array due to a combination of both array offset and boat pitch and roll.

A LBL system generally has an array of hydrophones with separations larger than the dimensions of a small boat, often at least tens of metres and as much as several kilometres. The array is sited on the bottom and the computed co-ordinates are related to some datum point that is also on the bottom, say one of the hydrophones. For the tracking application it is sufficient to know the positions of the hydrophones relative to each other in their own local grid. It is possible also to work on a world reference system, which means that once the array is calibrated on a local grid, the co-ordinates of this grid are transformed to provide absolute co-ordinates, for example by using the global positioning system (GPS), Milne [1]. The precision of a position fix in any LBL application depends on the calibration of the sea bed array.

## 4. POSITION FIXING ALGORITHMS

Navigation and tracking algorithms have been considered in great detail by many authors, for two and three (and sometimes more) transponders, beacons or hydrophones, in terms of transformation of co-ordinates, time and range repeatability, baseline errors, slant-range errors, incremental errors, multiplicative errors, transponder vertical displacement errors, platform motion, and so on, Cestone et al [2]. Concerning the transformation of co-ordinates, a point in space may be defined by three co-ordinates. Therefore, a suitable array consists of a hydrophone *triad;* if a click arrives at the hydrophones at times $t_1,t_2,t_3$, these times represent the co-ordinates of a unique point in the time domain and may be translated to x,y,z co-ordinates by multiplying each time by the sound velocity.

Position fixing algorithms are generally divided into four categories: (i) 2-D hyperbolic methods for a known depth, (ii) 2-D spherical methods for a known depth, (iii) 3-D hyperbolic methods for an unknown depth, and (iv) 3-D spherical methods for an unknown depth. Each of these categories can be sub-divided as follows: (i) algorithms giving direct solutions, Hardman & Woodward [4], Musa et al [5], Hodder & Woodward [8], and (ii) algorithms that use least squares calculations, Milne [1].

The algorithms giving direct solutions generate the co-ordinates of a position but without any check on accuracy, even though they are capable of giving millimetric precision if the correct assumptions are made, e.g. the lengths of the baselines are correct and the sound velocity value, measured or assumed, is accurate. In commercial applications, operators may have more confidence in a measurement technique if there is some in-built redundancy, e.g. if there are more transponders than are strictly necessary for the algorithms and if a number of measurements are made to give a best fit by a least squares method, but in tracking bio-sonar sources such as cetacean clicks it is generally not necessary to achieve such high accuracy. In general, the more hydrophones used the better the final position fix, but this also means more computation time, which is important if a practical compromise has to be reached for real time position fixing.

The principles of hyperbolic position fixing by such surface systems as Decca, Loran C and Omega have been applied for many years, but there have been few comparable underwater systems. The principle is to find the intersection of two or more hyperbolic lines to determine the x,y,z co-ordinates of an acoustic source; this is presented in more detail later. There are a number of algorithms available in the literature for both two-dimensional and three-dimensional position fixing, Milne [1], Hardman & Woodward [4].

Most position fixing systems use spherical methods. Readers are referred to an excellent text for details of algorithms and the corresponding computer programs for SBL, SSBL and LBL arrays, Milne [1].

## 5. CETACEAN TRACKING SYSTEM

Cetaceans have a highly developed sonar system used primarily for hunting fish by echo location. The sounds emitted can be heard as trains of short clicks when monitored with a hydrophone and a suitable receiver, Morphett et al [6]. There is now interest in tracking these animals to provide information about their behaviour, particularly near fishing nets. The basis of the tracking method is to determine the instantaneous position of an animal by detecting its sonar clicks. If a click arrives at three spatially separated hydrophones there are small time delays between the arrivals. By using a suitable algorithm these times can be translated into a 2-D position fix of the animal; using four hydrophones gives a 3-D position fix.

The general principles of diver or ROV tracking also apply to dolphin tracking, Milne [9], Kelland [10], Kelland [11], Woodward & Sharp [12], Woodward et al [13], but there are additional problems, mainly because a dolphin can swim much faster than a diver (up to 10 m/s) and because its click rate may vary from a few hertz to over one kilohertz. If two or more dolphins are echo-locating simultaneously then the individual clicks may not arrive at the hydrophones in the same sequence, which makes triangulation much more difficult.

The system design is shown in Fig.1. The essential function of the hardware is to log the arrival times of the clicks received by the three hydrophones $H_1$, $H_2$ and $H_3$. Each detected click is converted into a digital pulse by a 'click detector'; the pulse then operates a latch to log the instantaneous clock time under the control of an internal clock. As the same click arrives at the three hydrophones in turn, all three latches log the times of arrival. This enables the relative arrival times to be determined and the position of the dolphin to be computed.

The click arrival times are passed via a Digital Input-Output (DIO) interface card to a computer, which reads the outputs of the latches at regular intervals and builds up a record of click trains. The software analyses the three click trains, associates click arrivals on each channel with the corresponding clicks on the other channels, then computes the source of each click. As the clicks arrive, a succession of position estimates is built up, allowing the track of the dolphin to be determined.

The signals from the hydrophones can be transmitted to the receiver either directly via cables or indirectly via radio waves. The direct method has the advantage that the positions of hydrophones on the sea bed can be determined very accurately. The indirect method uses sonobuoys, which convert acoustic signals, detected underwater by a suspended hydrophone, to radio signals which are transmitted from an aerial attached to the electronic package floating on the surface. While these devices can be deployed easily from a boat, their positions move under the influence of wave action and tidal streaming. Another disadvantage is that, generally, the batteries need to be removed and replaced at regular intervals.

The inputs to the algorithm are the time delays between a click arriving at hydrophones $H_1$ and $H_3$ measured relative to its arrival at hydrophone $H_2$ ($t_{12}$ and $t_{32}$ respectively). The solution is a single estimate of the x,y position of the dolphin. Other constants required are the co-ordinates of the hydrophones and the velocity of sound in water. For a pair of delays the algorithm gives one of the following results: (i) a single solution; (ii) a dual solution, one of which is invalid for the corresponding pair of time delays; (iii) a dual solution, one real and one a 'ghost', both giving equally valid solutions; (iv) a solution or pair of solutions resulting from an iteration process, which is required when the solution to a quadratic equation would otherwise contain complex roots, Hardman & Woodward [4].

Whilst the dual solution is always mathematically valid, it is usually obvious in reality which of the two tracks is the correct one for an echo-locating dolphin, because of the physically impossible speeds at which the 'ghost' target moves. This led to the notion of a range circle, an area on the plot containing all points which the tracked dolphin could reach. Clearly the radius of this circle is dependent on its maximum speed $V_{max}$ (here, 10 m/s) and the time interval between successive clicks. Using these range circles can eliminate the dual solutions in the majority of cases.

The main problem of the software is to align three time-varying click trains on three channels without any previous information. However, mathematical analysis shows that if the origin of the acoustic source (the dolphin) is known then for a given click on Channel 2 there is a finite time window within which the same click should arrive on Channels 1 and 3. Generally, the time delays $t_{12}$ and $t_{32}$ change only gradually. Any given click would produce similar delays to the previous click. Analysis shows that the maximum rate of change of $t_{12}$ occurs when the dolphin is moving along the line between $H_1$ and $H_2$; a similar situation holds for $t_{32}$. This gives the expected time of arrival of a click on Channel 1 which relies only on the last value of $t_{12}$ and the current value of $t_2$, as shown in Fig. 2. The width of the time window can be appreciated by putting some simple numbers in: Assume $v$ to be 10 m/s, and $c$ (the velocity of sound in water) to be 1500 m/s. This means that for a dolphin clicking at 100 Hz ($\delta t$ = 10 ms) a click on either Channel 1 or Channel 3 can be predicted to arrive within a time window of 266 μs.

With clicks arriving every 10 ms there is no ambiguity about which click on Channel 1 corresponds to a click on Channel 2. If the dolphin's click rate is higher, $\delta t$ falls and the arrival window narrows accordingly, thus providing a self-compensating algorithm which could theoretically cope with any rate. The program is therefore capable of tracking a dolphin with no clues except for its 'initial position'. If a click is not found where it is expected, the program skips that click and attempts to look for the next one. If none of the succeeding few clicks are found when they are expected, the search windows gradually widen until they reach their maximum size. At this point the program is effectively carrying out a full *acquisition*. This restarts tracking from wherever the next source appears. The only further requirement of the system is to locate the starting point by itself; although this can be done it is not described here for reasons of brevity.

For convenience, the research described here has been done with bottlenose dolphins (*Tursiops truncatus*), initially using a static hydrophone array in a dolphinarium. Sea trials have also been carried out in the Moray Firth in northern Scotland. Three sonobuoys were deployed and clear signals were received on all three channels from dolphins echo locating at distances exceeding 300m, showing that the overall system is viable for future research. A more complex system for tracking cetaceans around a moving trawl at sea, but using similar principles, is described elsewhere, Connelly et al [7].

## 6. CONCLUSIONS

This paper has been written to provide an insight into the subject of acoustically tracking echo-locating cetaceans. It outlines the general principles and classifies the various techniques but has highlighted three particular applications, each having its own measure of engineering problems. The reader is presented with a reasonably comprehensive list of references from the literature in order to provide plenty of material for a follow-up study.

## 7. REFERENCES

1. P H MILNE, *Underwater acoustic positioning systems*, E. & F.N. Spon, London and New York, ISBN 0-419-12100-5 pp19-22 (1983)
2. J A CESTONE, R J CYR, G ROESLER & E St GEORGE Jr, Latest highlights in acoustic underwater navigation, *J Inst Navigation*, 2 p246 (1977)
3. R C SPINDEL, 'Acoustic navigation', *Oceanus*, 2 p22 1977
4. P A HARDMAN & B WOODWARD, 'Underwater location fixing by a diver-operated acoustic telemetry system', *Acustica*, 55, p34 (1984)
5. Z MUSA, N. MULLINEUX, J R REED & B WOODWARD, 'A simple problem in acoustic telemetry', *Int J Math Ed Sci Technol*, 15 p53 (1984)
6. N MORPHETT, B WOODWARD & A D GOODSON, 'Tracking dolphins by detecting their sonar clicks with an array of hydrophones', Proc IOA, 15 p50 (1993)
7. P R CONNELLY, B WOODWARD & A D GOODSON, 'A non-intrusive tracking technique for dolphins interacting with a pelagic trawl using a sparse array of hydrophones', Proc of IOA Underwater Bio-Sonar & Bio-Acoustics Symposium, Loughborough University, 16-17 December (1997)
8. T M HODDER & B WOODWARD, 'Algorithms for underwater position fixing', *Int J Math Ed Sci Technol*, 17 p407 (1986)
9. P H MILNE, 'Diver and submersible tracking using 3-D computer graphics', SUT Int Conf on Diving Technology *Divetech'81*, London, 24-26 Nov 1981
10. N C KELLAND, 'Calibration of an underwater distance measuring instrument', *Proc Inst Civ Engrs*, 58 p315 (1975)
11. N C KELLAND, 'A method of carrying out accurate planimetric surveys underwater', *Hydrographic J*, 2 p17 (1976)
12. B WOODWARD & H SHARP, 'Portable real time diver navigation system', *Ultrasonics*, 29 p81 (1991)
13. B WOODWARD, D A JOYCE & L NIAZI, 'Diver navigation with a programmable dive computer and an intelligent transponder array', *Acoustics Letters*, 16 p 62 (1992)

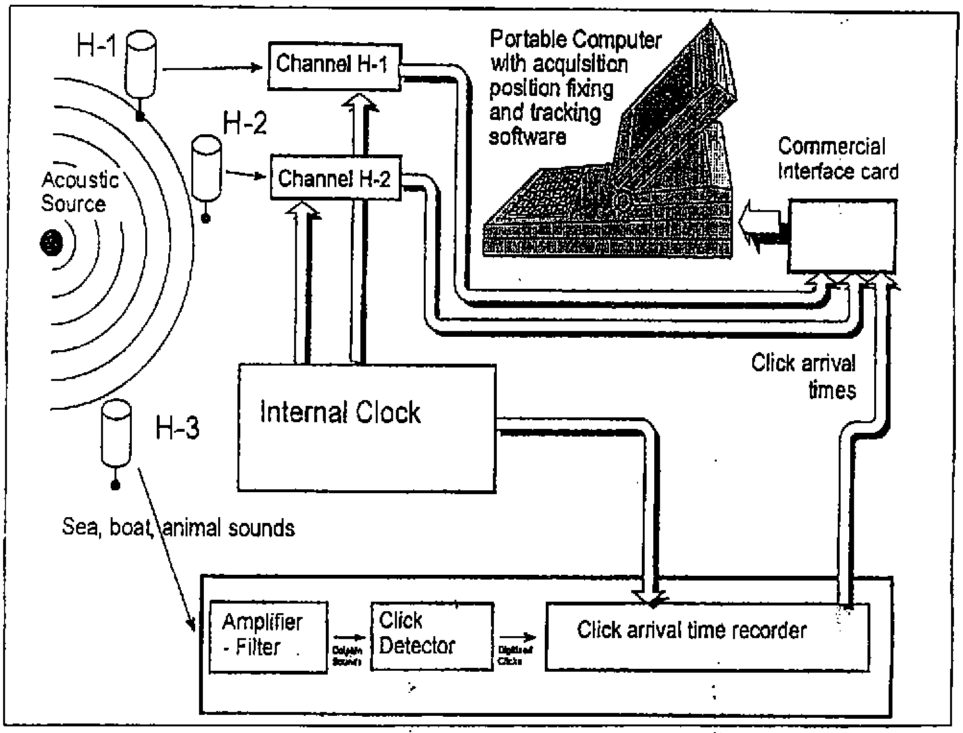


Fig. 1 Tracking system

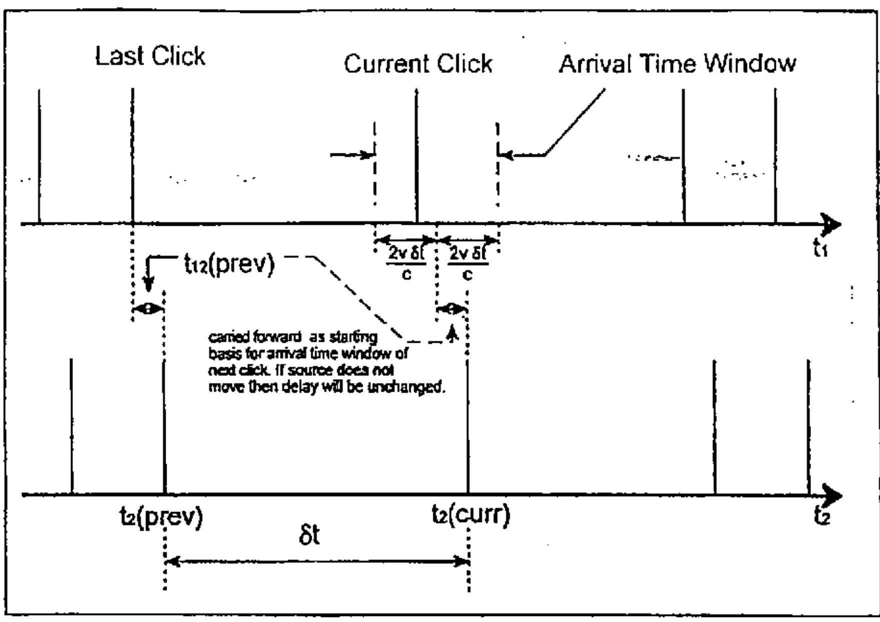


Fig 2 Alignment of clicks