Precise Sound Source Localisation of Dolphin Biosonar Pulse Transmissions

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Abstract – **Dolphins rely on auditory perception for survival and their biological sonars (or *biosonars*) equip them for life in marine environments. Dolphins probe their habitats using sequences of short underwater sound pulses (or *clicks*) for echolocation that enable them to navigate and avoid collisions with natural objects in the environment, and to detect and discriminate between prey, predators, and companions. In May 2009, sequences of biosonar click transmissions, which were emitted by *Tursiops aduncus* dolphins while swimming freely in their natural habitat, were recorded by a linear array of three widely spaced hydrophones located close to the sea floor in Jervis Bay (35° 07' S, 150° 42' E), New South Wales. In this paper, the hydrophone array output data for two sequences are processed for a 7.5 s observation period, where the arrival time differences of the biosonar signals at the hydrophones are measured to within 0.1 µs. The active biosonar of an individual dolphin is observed to operate in two modes – a *regular* mode, where the time interval between consecutive click transmissions is long (13-59 ms), followed by a *burst* mode, where there is a rapid succession of pulses with a short time interval (2-9 ms) between buzz signal transmissions. The source position of each click is localized by using the method of passive ranging by wavefront curvature. This nonintrusive acoustic source localisation method requires the differences in the arrival time data of the received pulses to estimate the range of the source from the centre of the array, as well as its bearing angle with respect to the longitudinal axis of the array. During the observation period, a dolphin is detected near the array. Initially, it is at a range of 28 m at the beginning of the regular click phase, and then it closes to a range of 13 m by the end of the buzz phase. Also, there is a rapid source bearing rate change during the buzz phase, with the bearing changing by 9° in 0.7 s. The instantaneous range and bearing of the moving source change continuously and vary by less than 13 cm and 0.07° respectively between interclick transmissions, and 2 cm and 0.06° between consecutive buzz signals. In addition, the arrival times at the hydrophones of click signals from a far dolphin are extracted from the data. For the 17 click transmissions that formed a sequence, the interclick time interval varies from 34 to 58 ms. The passive ranging by wavefront curvature method estimates the range of the far dolphin as 239±1 m with a bearing of 30.05° ± 0.01°. With this source localisation method, the precision of the source bearing estimates is within 0.01°, independent of the source range. The precision of the source range estimates varies from 1 cm for the near dolphin buzz sequence to 1 m for the far dolphin click sequence.**

I. INTRODUCTION

Whales and dolphins belong to the taxonomic order of *Cetacea*. The *Odontoceti*, or toothed whales, include the bottlenose dolphin, which are found worldwide in temperate and tropical waters. There are two currently recognised species of bottlenose dolphins, *Tursiops truncatus* and *Tursiops aduncus*. The latter appears to be restricted to coastal environments of the Indo-Pacific, Indian and Western Pacific Oceans, including south-eastern Australia [1]. Very little research has been undertaken on the vocal characteristics of the Indo-Pacific bottlenose dolphins (*Tursiops aduncus*), which are smaller in size (both in body length and weight) than *Tursiops truncatus*. It is the biosonar echolocation signals generated by this dolphin species that are of particular interest here. One coastal habitat of *Tursiops aduncus* is Jervis Bay which is a relatively enclosed embayment located approximately 200 km south of Sydney in New South Wales. With an area of 102 km², it is characterized by shallow waters (generally less than 20 m) and a shelving sea floor that gradually slopes towards the entrance, reaching maximum depths of around 40 m [1].

Dolphins must rely extensively on their auditory sensing skills for survival [2-5]. The underwater sound emissions of dolphins, which have been recorded and analysed both in open waters and in enclosed tanks, can be classified into two broad categories – *whistles* and *clicks*. Whistles, or narrowband frequency-modulated (FM) continuous tonal sounds, are generally emissions between 5 and 30 kHz that can last for several seconds and appear to be used for intraspecific communications [5]. Of specific interest here are the biosonar click transmissions, which are characterized by short duration impulsive sounds. The click pulse emissions are repetitive, thus forming a sequence or *click train*. The clicks can be used for echolocation to locate prey, avoid collisions with natural hazards and with each other, while swimming at night or in turbid water. Like bats, dolphins probe the environment with

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acoustic signals, enabling them to forage, avoid obstacles and predators, and orient themselves in the absence of light. Acoustic energy propagates in water more efficiently than other forms of energy such as electromagnetic, thermal and light energy, which are severely attenuated. Thus, dolphins with their active sonar capability are suited for life in aquatic environments. This capability is based on the emission of short clicks, usually in trains, and on the interpretation of their echoes, providing the echolocating odontocetes, and also their companions, with detailed information about their environment [6].

In May 2009, the click trains of free-ranging *Tursiops aduncus* dolphins in the wild were recorded using a collinear array of three widely spaced hydrophones located 1 m above the sea floor in Jervis Bay. Two types of pulse trains can be heard on audio replay of the data. Individual clicks can be resolved by the human ear because they are sufficiently separated in time. This occurs when the biosonar of the dolphin operates in the *regular* mode. During the *burst* mode, however, the time interval between pulses becomes so short that a single continuous *buzz* sound is perceived aurally, as the human ear can no longer resolve individual sound pulses [7, 8]. The passive ranging by wavefront curvature method [9], which is reviewed in Section II, is used to estimate the range and bearing of the source of the dolphin biosonar pulse transmissions. The analysis of the data and the results for localising the impulsive sources of underwater sound are covered in Section III. The biosonar transmissions from two dolphins are analysed, predominantly for a dolphin near the array and, to a lesser extent, for a far dolphin. A discussion on the results and findings of this paper in relation to other published work in the scientific literature comprise Section IV. The conclusions are listed in Section V.

Note that although passive sonar methods have been applied previously [8, 10-12] to study the properties of dolphin biosonars, the originality and advance of the present approach is the unprecedented precision to which an echolocating dolphin can be localised and observed in its natural habitat for complete click and buzz trains. The scientific technique implemented in this paper overcomes well-known problems experienced by other researchers when recording and analysing echolocation clicks from wild dolphins at sea [5, 10]. The present approach is unaffected by the following problems: (1) it is generally unknown which dolphin is producing the recorded clicks and how many animals are echolocating; (2) the peak-to-peak source level of clicks cannot be estimated with accuracy because the distance from the dolphin from the hydrophone is unknown; and (3) the direct path and multipath arrivals are not resolvable when the source and receiver are close (within 1 m) of the sea surface.

II. PASSIVE RANGING BY WAVEFRONT CURVATURE METHOD

Passive ranging techniques are used in sonar systems to localize sources that radiate acoustic energy in the underwater environment. Passive ranging by wavefront curvature, which uses a linear array of three equally-spaced sensors [9], is a special case of a general technique for locating a source that is based on intersections of hyperbolic curves defined by the time differences of arrival of a signal received at a number (≥3) of sensors [13]. The range R to the source from the middle sensor and the bearing (or conical angle) β with respect to the longitudinal axis of the array are given by

$$R = \frac{2d^2 - c^2(\tau_{12}^2 + \tau_{32}^2)}{2c(\tau_{12} + \tau_{32})} \quad (1)$$

$$\cos\beta = \frac{c^2(\tau_{32}^2 - \tau_{12}^2) - 2Rc(\tau_{32} + \tau_{12})}{4Rd} \quad (2)$$

where d is the intersensor separation distance, c is the speed of sound propagation in water, $\tau_{12} = T_1 - T_2$ is the difference in the times of arrival T_1 and T_2 of the signal at hydrophones 1 and 2 respectively, and $\tau_{32} = T_3 - T_2$ is the time-of-arrival difference at hydrophones 2 and 3. The nominal values of d = 14 m and c = 1521 m/s were advised for the present experiment [14]. The speed of sound propagation in seawater is affected by temperature variations in the water, by the degree of salt concentration (or salinity), and by the pressure (which increases with depth). In the present experiment, isospeed sound conditions prevailed [14].

With the present linear configuration of three hydrophones, there is a left-right ambiguity in determining the position of the source. This ambiguity would be resolved by including a fourth hydrophone in a known position on either side of the array axis in the horizontal plane.

A complexity of this passive ranging method is the requirement for the sensors to be collinear. A mismatch between the assumed (nominal) position and the actual position of the middle sensor, for instance, would introduce a bias error that would adversely affect the accuracy of the range and bearing estimates. For example, a bowing of array towards the source would lead to the range being underestimated [15, 16].

III. DATA ANALYSIS AND RESULTS

A. Near Dolphin Click and Buzz Signals

1. Click Signal Waveforms

Each hydrophone used in the experiment had a flat response for the frequency band 1 – 100 kHz. The output of each hydrophone is sampled every 4 μs, which equates to a sampling rate of 250 kHz. (Note that 1 μs represents $1\text{x}10^{-6}$ s.) The analogue-to-digital converter for each hydrophone output

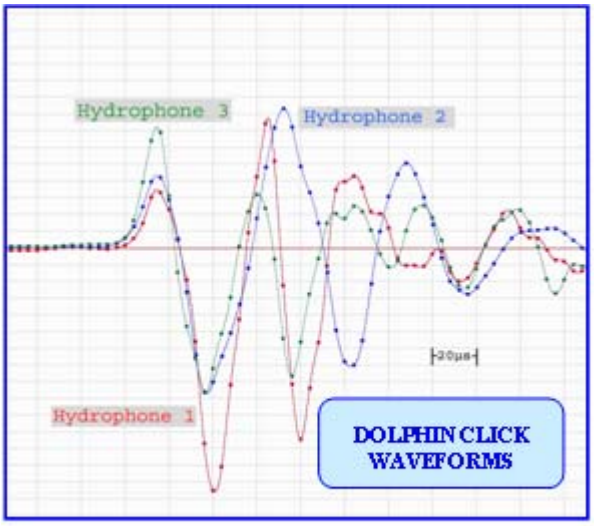


Fig 1. Waveforms showing the variation with time of the amplitude of a dolphin click signal received at hydrophones 1, 2 and 3.

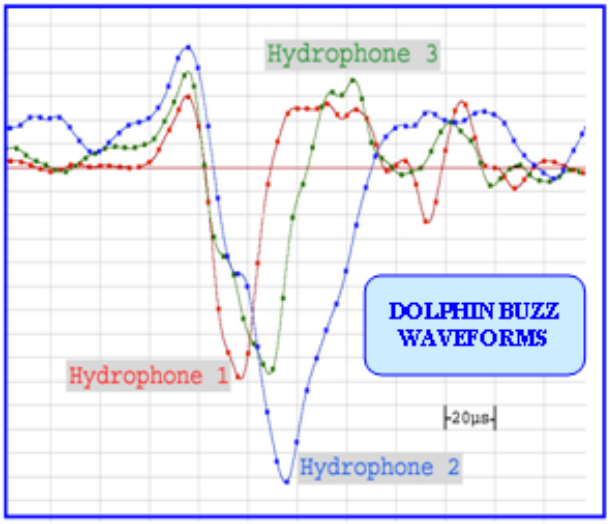


Fig 2. – Waveforms showing the variation with time of the amplitude of a dolphin buzz signal received at hydrophones 1, 2 and 3.

has 16 bit quantisation. Figure 1 shows examples of the signal waveforms received at each of the three hydrophones with each sample point being enclosed by a coloured rectangle: ■ ■ and ■ for hydrophones 1, 2 and 3 respectively. These waveforms are representative of a single dolphin *click* signal that is received at each of the hydrophones. For purposes of comparison, the waveforms are shifted in time so that they are aligned with respect to the first (positive pressure) peak. The temporal variations in the shapes of the received waveforms are consistent with dolphin biosonar click signals having directional properties. In other words, the outgoing biosonar waveforms vary with the angle of transmission. These click waveforms have multiple compression/rarefaction cycles.

2. Buzz Signal Waveforms

Similarly, time-shifted waveforms for a *buzz* signal received at each of the hydrophones are shown in Fig. 2. These waveforms are characterized by a small positive pressure peak that is followed by a deep rarefaction (negative pressure) trough with the pressure difference between compression and rarefaction becoming smaller for subsequent cycles. The width of the trough varies from 36 μs (for hydrophone 1) to 80 μs (for hydrophone 2). Like the click signals, the dolphin biosonar buzz signal waveforms vary with the angle of transmission.

3. Time of Arrival Measurements

The arrival time of a dolphin biosonar transmission at each hydrophone is refined by interpolating between the sample points. Figure 3 shows a time dilated (expanded) view of the first peak of a dolphin sonar signal received at hydrophone 2. Although the sample points are 4 μs apart, the arrival time of the peak, denoted by T_2, can be measured to within 0.1 μs.

4. Time Interval between Dolphin Click Transmissions

The time interval between dolphin sonar click transmissions, which is commonly referred to as the interclick interval [5], is given by the difference between the arrival times of consecutive clicks. The variation with click number for a complete click train of 247 biosonar transmissions is shown in Fig. 4(a). The variation with click number of the interclick interval undulates between 13 and 59 ms. (Note that 1 ms represents $1x10^{-3}$ s.) For the sequence of 291 buzz signals, the time interval between the underwater sound pulse transmissions progressively decreases from an initial value of about 7 ms to less than 2 ms before increasing again to a maximum of 9 ms at the end of the buzz sequence – see Fig. 4(b).

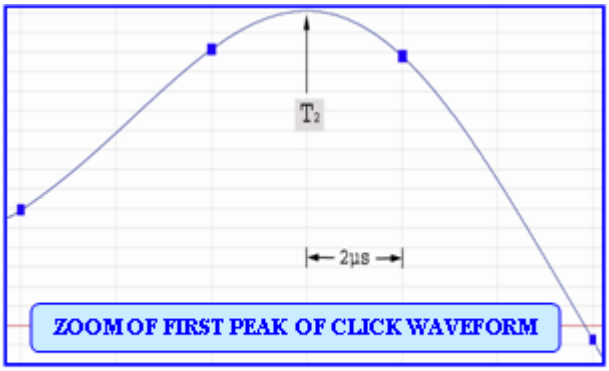


Fig 3. Time axis expansion for refining the estimate of the arrival time T_2 of the first peak of a dolphin click signal at hydrophone 2.

5. Signal Source Localisation during Click and Buzz Phases

The source of the biosonar signal transmissions is localised by first calculating the differences in the arrival times of the underwater sound pulses at the hydrophones. For example, when the refined time of arrival measurement method (above) is applied to the first peak of each of the waveforms shown in Fig. 1, then the observed arrival times of the dolphin click signal at hydrophones 1, 2 and 3 are given by $T_1 = 10\,\text{min} : 13.0824344\,\text{sec}$, $T_2 = 10\,\text{min} : 13.0747186\,\text{sec}$ and $T_3 = 10\,\text{min} : 13.0705265\,\text{sec}$. The arrival times: T_1, T_2, T_3 for each click are used to calculate the differences in the arrival times: $\tau_{12} = T_1 - T_2$ and $\tau_{32} = T_3 - T_2$. These values are then substituted in the passive ranging by wavefront curvature equations (1) and (2) to provide estimates of the source range R = 19.93 m and the source bearing β = 137.21°.

For the click sequence, the source range estimates indicated that the dolphin was near the array – see Fig. 5(a). The click source is tracked in range and bearing throughout the click train. The dolphin approaches the array causing the source range to decrease from its initial range of 28.1 m to a final range of 13.7 m at the end of the click train. For the click sequence, the average radial velocity of the dolphin is about 2 m/s. Also, the source bearing increases from its initial value of 133.8°, to a maximum value of 138.0° before decreasing to 129.7° at the end of the click train. After a delay of 161 ms, the buzz phase begins. During the buzz sequence, the source range continues to decrease from 13.54 m to 13.11 m with the bearing decreasing from 127.7° to 118.9° – see Fig. 6. The respective precisions of the range and bearing estimates are within 1 cm and 0.01°.

B. Far Dolphin Click Signal Sequence

1. Waveforms

As well as the click and buzz sequences emitted by a dolphin near the array, another dolphin click sequence is observed on the outputs of all three hydrophones. Figure 7 shows the waveforms of one of these click signals, which have been time-shifted so that the maxima are aligned. There is a good match between the waveforms on all three hydrophones, which suggests that the dolphin is far from the array as the three hydrophones are ensonified by the same part of the dolphin's sonar transmission (sound projection) beam.

2. Source Localisation of Far Dolphin Click Signals

For the 17 click transmissions that comprised the sequence, the interclick time interval varied from 34 ms to 58 ms. The passive ranging by wavefront curvature method is used to localise the source of the biosonar click transmission sequence. The range and bearing estimates are averaged and the respective standard deviations calculated to provide a source range estimate of 239±1 m with a bearing range estimate of 30.05° ± 0.01° for the far dolphin.

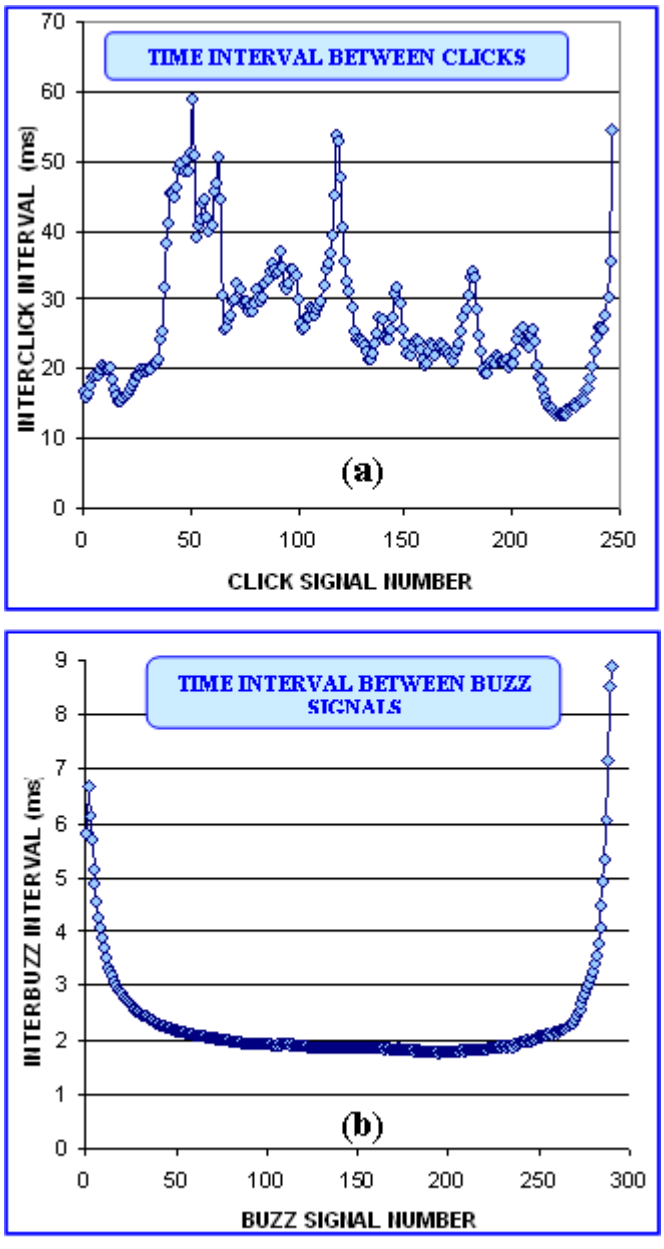
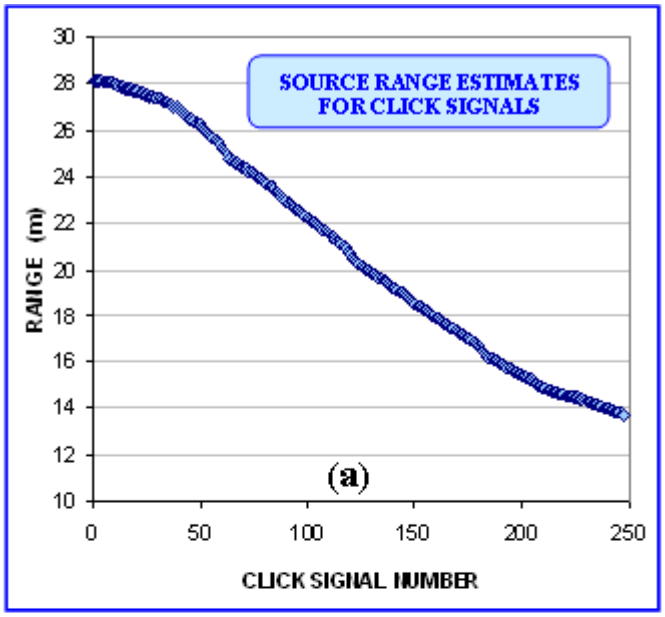


Fig 4. Time interval between consecutive (a) click signals and (b) buzz signals received at hydrophone 2.



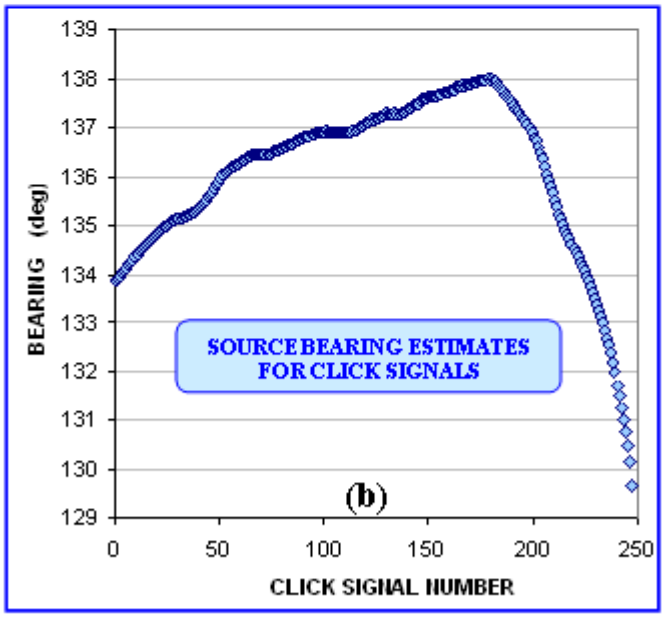
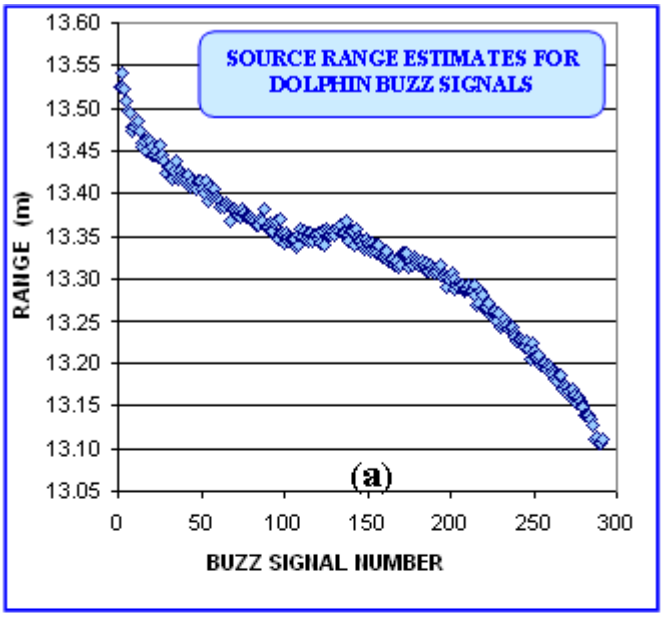


Fig 5. Variation during the near dolphin click sequence of source (a) range and (b) bearing.



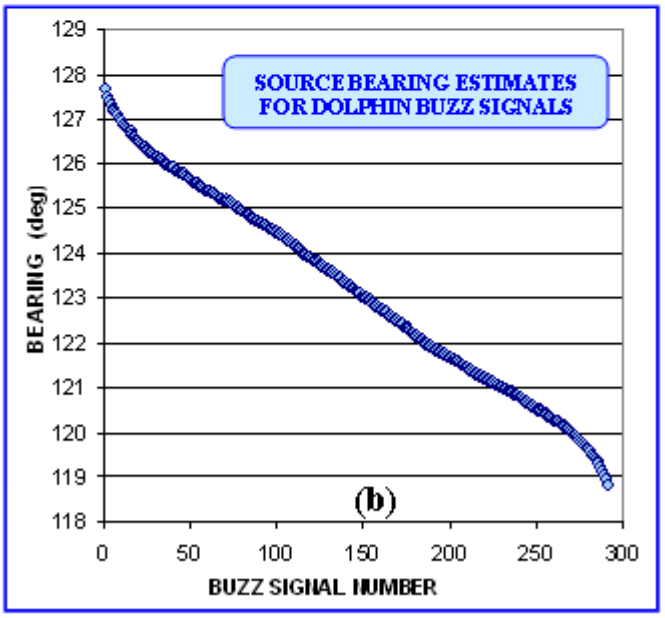


Fig 6. Variation during the near dolphin's buzz sequence of source (a) range and (b) bearing.

Fig 7. – Waveforms showing the variation with time of the amplitude of a far dolphin click signal received at hydrophones 1, 2 and 3.

IV. DISCUSSION

A. Waveforms

For the *Tursiops aduncus* dolphins considered here, the duration of the click signals is ≈100 µs for the far dolphin and ≈200 µs for the near dolphin. The time duration (or period) of the *peak energy cycle* is 25 µs (40 kHz) for the far dolphin and 40 µs (25 kHz) for the near dolphin. During the buzz phase, the period of the peak energy cycle varies from 40 µs to 80 µs (12.5-25 kHz). The echoloclation signal characteristics of other odontocetes are comparable including *Tursiops truncatus* dolphins where the echolocation clicks have between four and eight cycles and durations of 40-70 µs [17]. Also, durations of 50-80 µs appear in the scientific literature for both Atlantic bottlenose dolphins (*Tursiops truncatus*) and Pacific bottlenose dolphins (*Tursiops gilli*) [5]. For the harbour porpoise (*Phocoena phocoena*) and Dall's porpoise (*Phocoenoides dalli*), the click signal durations are longer 130-260 µs and 180-400 µs respectively [5]. For *Mesoplodon densirostris* beaked whales, rather than directly measuring the duration of the regular click transmissions, echo durations from ensonified incoming prey had durations of 250-320 µs [18].

The spatial variation of the click and buzz signal waveforms for the near dolphin, which are received at the three spatially distributed hydrophones, is consistent with the emitted echolocation signals of dolphins and other odontocetes being known to be directional, with the waveform, frequency content, and amplitude of the clicks varying with the orientation of the dolphin [5]. The transmission beam patterns in the vertical and horizontal planes for *Tursiops truncatus*, for example, have been measured by other researchers using an array of hydrophones in the vertical and horizontal planes [5]. As the angle departs from the beam axis, the signals in the time domain become progressively distorted relative to the signal on the major axis. The click projection system of dolphins is directional, with a 3 dB beamwidth of approximately 10° in both the vertical and horizontal planes for *Tursiops truncatus*. In the horizontal plane, the beam is pointed directly ahead of the dolphin in the same direction as the longitudinal axis of the dolphin. The echolocation signals are projected at an elevation angle of 5-10° above the dolphin's head in the vertical plane.

B. Time Interval between Consecutive Biosonar Transmissions

The time interval between successive biosonar signal transmissions for the complete sequence of *Tursiops aduncus* dolphin click signals slowly fluctuates in a periodic manner between a minimum value of 13 ms and a maximum value of 59 ms. This periodic variation in interclick interval also occurs with *Tursiops truncatus* dolphins [5]. Thus, a common characteristic of *Tursiops aduncus* and *Tursiops truncatus* dolphins is the cyclic variation in click interval from pulse to pulse, whereby the interclick interval increases to a peak, then decreases, and once again increases, leading to a cyclic pattern of maxima and minima [5]. The interclick intervals for the *Tursiops aduncus* dolphin (13-59 ms) are shorter than the time intervals between regular click transmissions for other species of dolphins: *Tursiops truncatus* 100-150 ms [19], also 80-190 ms [20], Hawaiian spinner dolphins *Stenella longirostris* 60-160 ms [10], and for Blainville's beaked whales (*Mesoplodon densirostris*): 200-500 ms, with an emphasis around 400 ms [18].

For the buzz phase of the *Tursiops aduncus* dolphin, the time interval between the emission of consecutive buzz signals decreases rapidly from 7 ms to 2 ms where it remains for most of the buzz phase before increasing to 9 ms at the end of the buzz pulse sequence. This 2 ms time interval between successive buzz signal transmissions is much shorter than the interclick interval for a regular click sequence. Also, unlike the regular click sequence, the time interval between buzz signal transmissions does not have a periodic fluctuation but remains constant. For other odontocetes, the time interval between the consecutive buzz signals varies between 1.7 ms and 3.3 ms for the harbour porpoise (*Phocoena phocoena*) dolphins [21], 2-8 ms (with a mean of 3.5 ms) for Hawaiian spinner dolphins *Stenella longirostris* [10], and for beaked whales, the time intervals vary between 5 ms and 20 ms [18].

With the foraging strategies of both *Tursiops truncatus* and *Stenella frontalis* (Atlantic spotted dolphins), two phases of echolocation are *search* and *approach*. In the search phase, echolocation interclick intervals are >5 ms until the approach

phase, when, after detection of the prey, the interclick interval decreases to 2 ms with the postural behaviour of the dolphin described as pointing into the sandy seafloor and dislodging fish with its rostrum [22]. Observations of dolphin behaviours during buzz phases include courtship, discipline and juvenile play, aggression, and exploration involving focused attention on inanimate object such as floating debris and plant life. Interestingly, buzzing in these social contexts is not believed to have an echolocation function according to current sonar theory [22].

C. Passive Sonar Ranging of Dolphin Biosonar Transmissions

The present experiment was able to achieve centrimetric precision in the source range estimates by combining an array of widely spaced hydrophones (d=14 m) with precise (0.1μs) arrival time measurements. Another method for localising dolphin sonar transmissions by applying hyperbolic ranging algorithms to signal arrival time information includes a configuration of four hydrophones spaced 30 m apart at the vertices of a tetrahedron to localise spinner dolphins [11]. Due to the large size of the array, however, the directional echolocation clicks were seldom recorded at all four hydrophones. Also, the arrival-time error was 0.1 ms (which is large when compared with 0.1 μs in the present experiment). This results in errors in the source position of up to 1 m, when the source was within the boundaries of the 30-m array. At 55 m from the centre of the array, maximum potential spread in the source range was nearly 10 m; at 80 m, the range error spread was 25 m; and at 300 m, a scatter of over 150 m in range estimates was possible [11].

Another acoustic source localisation system, which was used to range echolocation signals from dolphins, consisted of an array of four hydrophones arranged in a symmetrical star configuration, with one centre hydrophone and three extending arms spaced 120° apart [12]. At source ranges of 25 m, the standard deviation in the range estimates was 43 cm due to an intersensor spacing of 0.61 m, which is small when compared with the 14 m spacing in the present experiment.

V. CONCLUSION

Passive ranging by wavefront curvature is a practical nonintrusive technique for studying the behaviour of individual echolocating odontocetes in their natural habitats. The combination of precise (0.1μs) arrival time measurements and widely-spaced (14 m) hydrophones in a collinear array configuration enables the source of dolphin biosonar click transmissions to be localised with a (range independent) bearing precision of 0.01° and with centimetric precision at ranges of about 25 m, increasing to 1 m at about 250 m. The addition of a fourth off-axis hydrophone would resolve the left-right ambiguity source localisation problem.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the guidance and advice of Dr Doug Cato (University of Sydney Institute for Marine Science, also with the Defence Science and Technology Organisation) and the technical support of Jane Cleary (Defence Science and Technology Organisation). The author wishes to thank Max Carpenter (Jervis Bay Underwater Sound Range, Navy Systems Command), who was responsible for the operation of the underwater acoustic sensing array and the digital data acquisition during the experiment. Finally, the author is grateful to Sophia Giardini (Sydney University) for proof reading and improving the manuscript.

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