One-hydrophone method of estimating distance and depth of phonating dolphins in shallow water

Roland Aubauer,[a] Marc O. Lammers, and Whitlow W. L. Au
Hawaii Institute of Marine Biology, University of Hawaii, P.O. Box 1106, Kailua, Hawaii 96734

(Received 7 September 1999; accepted for publication 25 January 2000)

Previous attempts at localizing cetaceans have generally used multiple hydrophone arrays and multichannel recording systems. In this paper, a low-budget localization technique using only one hydrophone is described. The time delays of the signals traveling via the surface and bottom reflection paths to the hydrophone, relative to the direct signal, are used to calculate the distance and the depth of a phonating animal. Only two additional measures, the depth of the bottom and hydrophone, have to be taken. The method requires relatively shallow waters and a flat bottom surface. Echolocating and burst pulsing Hawaiian spinner dolphins (*Stenella longirostris*) at the Waianae coast of Oahu, Hawaii, were localized over different bottom substrates. A tracking range of up to 100 m was achieved. The accuracy of the method is estimated by the total error differential technique. The relative distance estimation error is below 35% and the absolute depth error below 0.7 m, so that the location method is sufficiently precise for examining source levels in our study area. Because of its simplicity, the method ideally complements sound recordings and visual sightings of marine mammals and could lead to a better understanding of the nature and use of click trains by dolphins. [S0001-4966(00)00605-6]

PACS numbers: 43.80.Ka, 43.80.Lb [FD]

INTRODUCTION

Compared to most animals, dolphins possess highly developed hearing and sound production capabilities. Dolphins are able to emit tonal and clicklike sounds from a few hundred Hz to about 160 kHz and can perceive sound in the same frequency range. Furthermore, dolphins possess a sophisticated echolocation system that they use for orientation and prey capture. Therefore, it is not surprising that many studies of these marine mammals focus on their acoustics.

In order to obtain better knowledge about the use and function of emitted signals, it is necessary to determine the position of the sound-producing animal relative to the sound recording hydrophone. The range of the calling dolphin is the key to determining the source level of specific signals. The source level of emitted signals is a fundamental parameter necessary to gain insight about dolphin echolocation and social behavior in the wild.

Previous attempts at localizing cetaceans have generally used multiple hydrophone arrays and differences in time-of-arrival measurements. Hydrophones have been towed from a ship as a linear line array, floated independently with an anchored line, or mounted on the sea bottom. At least four hydrophones in an appropriate arrangement are necessary to determine the three-dimensional location of a calling animal by evaluating the travel time differences of the incoming sound. A fifth hydrophone is necessary to resolve the spatial ambiguity of two possible positions (Spiesberger and Fristrup, 1990). All of these methods use multichannel recording and signal evaluation that require expensive and highly sophisticated technical equipment. Recently, Cato (1998) described three relatively simple methods for estimating source levels and distances of marine animal sounds. Two methods make uses of arrival time and level differences of the signals received by two separated hydrophones. The third method estimates source range from the levels and arrival times of the direct and surface reflected signals.

This paper describes another technique to localize marine animals based on arrival time difference measurements of the direct, the surface, and the bottom reflected signals. The method requires only one hydrophone and determines the distance and depth of the animal. From the distance estimation the source level of emitted signals can also be estimated. Under certain conditions this new method gives significantly better distance, depth, and source level estimates than the methods of Cato.

I. MULTIPATH PROPAGATION IN SHALLOW WATER

Sound in the dolphin frequency range propagates relatively well under water, due to a low absorption loss of less than 0.04 dB/m for frequencies less than 160 kHz and water temperatures less than 25 °C. At the air–water interface and at the water–bottom interface sound is reflected relatively well, because of the large differences in acoustic impedance Z at the interfaces. The reflectivity R is related to the acoustic impedance Z of the substance and of water Z_w,

$$R=\frac{Z\cdot\sin\varphi_w-Z_w\cdot\sin\varphi}{Z\cdot\sin\varphi_w+Z_w\cdot\sin\varphi},\qquad(1)$$

where φ_w is the incident and reflected angle and φ the transmitted angle, and both angles are related by Snell's law,

$$\frac{\cos\varphi_w}{\cos\varphi}=\frac{c_w}{c},\qquad(2)$$

where c_w is the sound velocity in water and c is the sound velocity in the other medium (see Fig. 1). Typical values of the impedance and reflectivity of various substances in sea water under the assumption of normal sound incident are

[a]Author to whom correspondence should be addressed: Mussumer Kirchweg 174, D-46395 Bocholt, Germany.

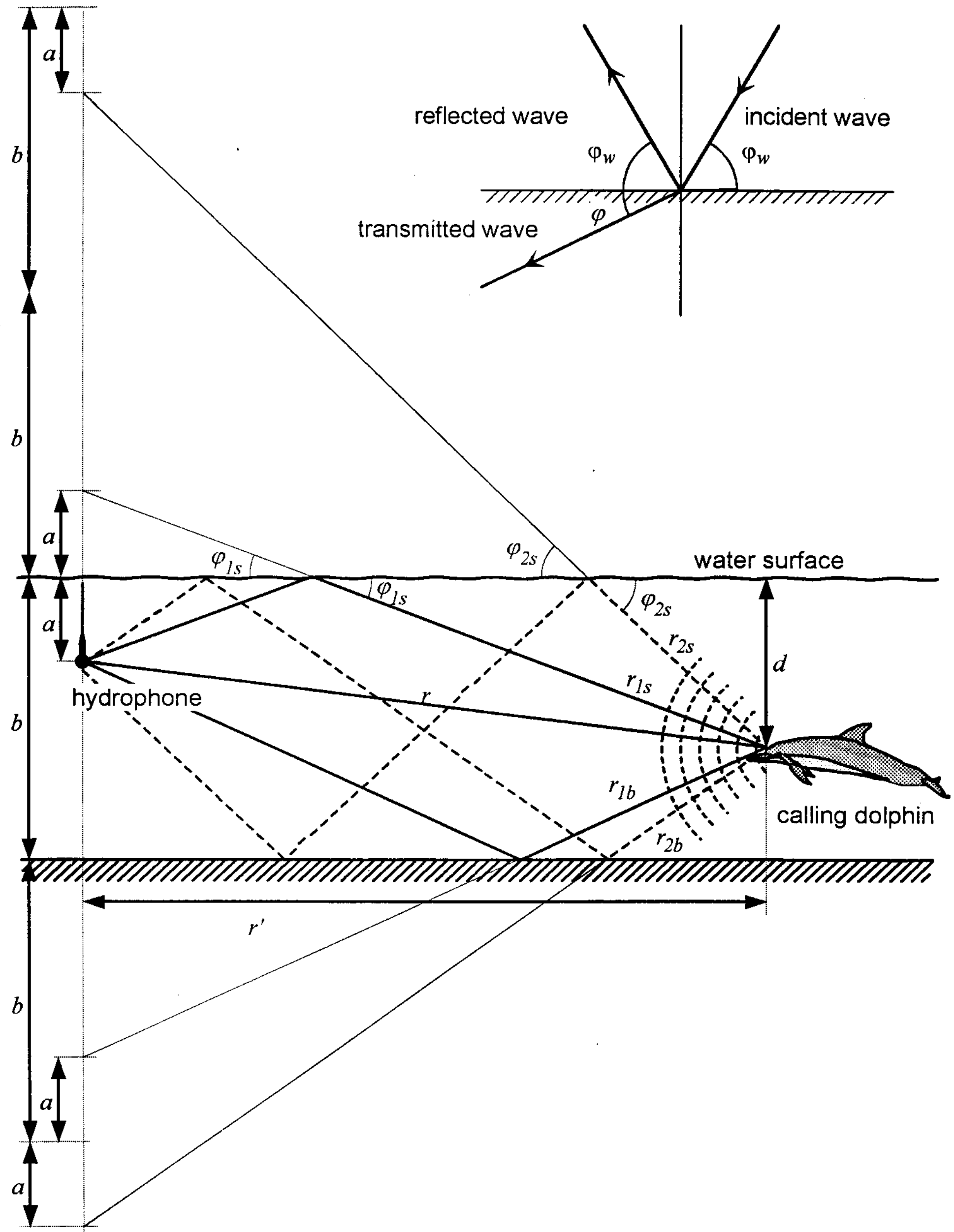

FIG. 1. Multipath propagation in shallow water with a flat ground surface. (——) Direct and first order ($n=1$) propagation paths. (– – –) Second order ($n=2$) propagation paths. Thin and straight lines starting at the calling dolphin and ending above the water surface and below the sea ground illustrate the construction of Eqs. (4)–(7). The lengths of these lines correspond to the lengths of the shown first and second order propagation r_{1s}, r_{1b}, r_{2s}, and r_{2b}.

given in Table I. Since the angle of refraction φ cannot be less than 0° a critical angle can defined as

$$\varphi_{w_c} = \arccos \frac{c_w}{c}, \tag{3}$$

and the sound is completely reflected for angles $\varphi_w \leqslant \varphi_{w_c}$. For reflection angles φ_w less than the critical angle, the reflection coefficient R becomes complex. The phase of the bottom reflected signal relative to the source signal is dependent on the reflection angle and moves from 0° ($\varphi_w \geqslant \varphi_{w_c}$) to 180° ($\varphi_w \leqslant \varphi_{w_c}$). For sand (assuming a sound velocity of 1710 m/s) the critical angle is around 28°. No critical angular phenomena occur for the surface reflection since the sound velocity in air is lower than that in water.

TABLE I. Acoustic impedance and reflectivity of various substances in sea water. The reflectivity values are for normal incidence on an ideal plane interface between water and the material (Stephens, 1970).

Substance	Impedance in $(\mathrm{N/m^2})/(\mathrm{m/s})$	Reflectivity in %
Air	$0.0004 \cdot 10^6$	−100
Sandstone	$7.6 \cdot 10^6$	66
Granite	$16 \cdot 10^6$	82
Sea water	$1.54 \cdot 10^6$	···

In shallow water and for relatively short ranges (water depth $b < 25$ m, range $r < 100$ m) sound propagation is approximately linear, since ray deflection can be neglected because of the relatively homogenous speed of sound in the water column (Clay and Medwin, 1977). In addition, waters have to be calm, since the surface path of the sound can be changed drastically by waves, especially when the calling animal is close to the water surface.

Different orders of multipath propagation must be considered. The order number n indicates the total number of signal reflections at the air–water and water–bottom interfaces before the signal arrives at the receiver. The propagation path with the initial reflection at the air–water interface is called the surface path, while the path with the first reflection at the water–bottom interface is called the bottom path. Cases with $n>1$ indicate multiple reflections between the surface and bottom interfaces (see Fig. 1). Equation (4) describes the length r_{ns} of the surface paths while Eq. (5) describes the length r_{nb} of the bottom paths, for orders $n\geqslant 1$. The length of the direct sound path is r, while the depth of the receiving hydrophone, the water, and the dolphin are a, b, and d, respectively. The horizontal separation between the sound source and the receiver is r'.

$$r_{ns}=\sqrt{r'^2+h_{ns}^2}, \tag{4}$$

$$r_{nb}=\sqrt{r'^2+h_{nb}^2}, \tag{5}$$

where

$$r'=\sqrt{r^2-(d-a)^2}, \tag{6}$$

$$h_{ns}=\begin{cases} b\cdot(n-1)+a+d, & n \text{ odd} \\ b\cdot n-a+d, & n \text{ even}\end{cases}, \tag{7}$$

$$h_{nb}=\begin{cases} b\cdot(n+1)-a-d, & n \text{ odd} \\ b\cdot n+a-d, & n \text{ even}\end{cases}. \tag{8}$$

The path lengths r_{ns} and r_{nb} become longer with increasing reflection order, so that signal components traveling on higher-order reflection paths always arrive later at the receiver than lower-order reflections. In addition, the reflection angles φ_{ns} and φ_{nb} increase with the reflection order n [Eqs. (9) and (10)]. Within one reflection path the reflection angles are constant because of Snell's law of reflection,

$$\varphi_{ns}=\arctan\frac{h_{ns}}{r'}, \tag{9}$$

$$\varphi_{nb}=\arctan\frac{h_{nb}}{r'}. \tag{10}$$

The increasing reflection angles with higher-order reflection paths result in large differences in signal amplitudes at the hydrophone because of the transmission beam pattern of dolphin clicks [the half-power angle is less than 10° for an echolocating *Tursiops truncatus* (Au, 1980)]. In addition, the signal is attenuated and spread with every reflection, especially when the reflective surface is rough and of lower reflectivity like the water–bottom interface. Higher-order reflections ($n\geqslant 2$) are therefore strongly attenuated and can be observed only for high source levels where an animal is directed at the hydrophone and for dolphin to hydrophone distances much larger than the water depth. For these large distances the reflection angle is relatively small, so that the amplitudes of the higher-order reflections are not attenuated much compared to the direct signal.

II. SOUND SOURCE LOCALIZATION

The measurement of arrival time differences between the direct and the indirect signals received with one hydrophone provides an easy way to determine the distance and depth of calling animals, assuming the propagation conditions are known and constant. At the study site, approximately 200–1000 m offshore along the Waianae coast of Oahu, Hawaii, the sea floor in certain areas is almost evenly flat (less than a 1-m drop in depth per 100-m of distance) and consists mainly of basaltic rock with some sandy patches, almost without any corals or other outcrops. Spinner dolphins (*Stenella longirostris*) use this shallow coastal area (depths below approximately 30 m) mainly during the day for resting and socializing purposes, after returning from nighttime feeding in open waters. During socializing periods, these dolphins are acoustically very active and produce many echolocation click trains, burst pulse sounds, and whistles. Recordings used in this study were only made on calm days (Sea State one or less) from an anchored boat in waters with low current conditions. Depth at the actual study site was determined using a hand-held, personal dive sonar (Under Sea Industries).

Dolphin signals were recorded using a custom-made spherical PZT piezoelectric hydrophone with a flat (±5 dB) frequency response from 10 to 160 kHz. The hydrophone was connected to a portable broadband data acquisition system, which digitized the incoming signal at a sampling rate of 260 kHz at 12-bit resolution. This recording system is composed of a preamplifier, analog filters, and a data-acquistion PCMCIA card plugged into a notebook computer that allows pretrigger data acquisition (Au *et al.*, 1999).

A burst pulse sequence from a Spinner dolphin is shown in Fig. 2 with the spectrogram representation in Fig. 2(a) and the time-domain representations in Fig. 2(b) and (c). The sequence is fairly typical of most burst pulse sequences recorded at the study site. It is relatively short, contains very broad band clicks with peak frequencies between about 15 kHz to more than 130 kHz and has interclick intervals of 6 to 9 ms. The magnification of click number five in Fig. 2(c) reveals the key property of this sequence and many other click trains recorded at this study site, namely, initial clicks are followed by up to four (three in Fig. 2) more clicks, lower in amplitude and equal or longer in duration. The time delays between the initial and subsequent clicks are consistent over the entire sequence, 404, 869, and 1808 μs (±4), respectively.

Assuming that click repetitions are caused by multipath propagation of the emitted dolphin sounds and not by the dolphin itself, the distance and depth of the dolphin can be determined by measuring the time delays, τ_{nb} and τ_{ns}, of the trailing clicks relative to the initial click and by using Eqs. (4) and (5). The distance r for signals with $n=1$ path is given by

$$r=\frac{\left(\frac{c\cdot\tau_{1b}}{2}\right)^2+b\cdot(a-b)-\left(\frac{c\cdot\tau_{1s}}{2}\right)^2\cdot\left(1-\frac{b}{a}\right)}{\frac{c\cdot\tau_{1s}}{2}\cdot\left(1-\frac{b}{a}\right)-\frac{c\cdot\tau_{1b}}{2}}. \tag{11}$$

The corresponding depth d is given by

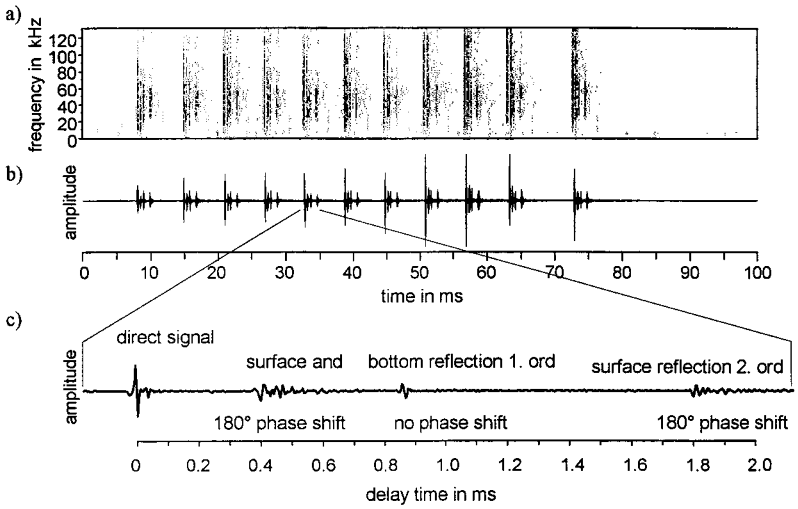

FIG. 2. (a) Spinner dolphin burst pulse signal with multipath propagation recorded in shallow waters along the Waianae Coast of Oahu. The spectrogram of the burst signal sequence shows the broadband nature of these sounds. (b) Complete burst pulse sequence in the time domain, interclick interval 5–10 ms. (c) Enlargement of a single burst pulse with first- and second-order multipath propagation.

$$d=\frac{\left(\frac{c\cdot\tau_{1b}}{2}\right)^2+\left(\frac{c\cdot\tau_{1b}}{2}\right)\cdot r}{a-b}+b. \tag{12}$$

The uncertainty of assigning the measured time delay to the correct propagation paths can be resolved in many cases considering the phase relationship of the click repetitions. Sound traveling from a higher to a much lower density medium (the water–air interface) is reflected at the medium boundary with a 180° phase shift, whereas sound traveling from a lower to a higher density medium (the water–bottom interface) is reflected with a phase shift between 0 and 180°, depending on the angle of reflection [see Eq. (1) and Fig. 2(c)]. The 180° phase shift can be detected easily at the onsets of the signal repetitions because the first and second cycles are inverted compared to the direct signal (see Fig. 2). The order of the propagation path can be determined by the time of arrival, since higher-order paths are considerably longer so that they always arrive later than the lower ordered signals.

Two reflection signals are necessary for localization. Further reflections, like the third trailing click in the example shown [Fig. 2(c)], are redundant but can be used to verify the method or to increase the accuracy of the localization through error correction.

III. ERROR ESTIMATION

The accuracy of the localization method can be estimated with the total error differential of the distance and depth functions. The total error differential is the sum of the partial derivatives of all variables multiplied by the error bounds of the individual measurements [see Eqs. (13) and (14)]. The method is used for obtaining an upper bound on the location error considering the measuring errors of the individual variables (Bronstein and Semendjajew, 1983).

In the following analysis, measurement errors of $|\Delta a| = 0.1$ m for the hydrophone depth a, $|\Delta b| = 1$ m for the water depth b, $|\Delta c_w| = 5$ m/s for the sound velocity c_w in water, and $|\Delta\tau| = 8$ μs for the time delays τ_{1b} and τ_{1s} are assumed. Furthermore, a water depth of $b = 12$ m, typical at the study site, and a hydrophone depth of $a = 3$ m are used. The distance r and the depth d of the dolphin are determined with Eqs. (11) and (12). Only the first-order $(n = 1)$ propagation paths are used. The upper bound of the relative distance error $\Delta r/r$ is established using the total error differential Δr,

$$\frac{\Delta r}{r}=\frac{\left|\frac{\partial r}{\partial a}\right|\cdot|\Delta a|+\left|\frac{\partial r}{\partial b}\right|\cdot|\Delta b|+\left|\frac{\partial r}{\partial c_w}\right|\cdot|\Delta c_w|+\left|\frac{\partial r}{\partial \tau_{1b}}\right|\cdot|\Delta\tau|+\left|\frac{\partial r}{\partial \tau_{1s}}\right|\cdot|\Delta\tau|}{r}. \tag{13}$$

The upper bound of the absolute depth measurement corresponds with the total error differential Δd,

$$\Delta d=\left|\frac{\partial d}{\partial a}\right|\cdot|\Delta a|+\left|\frac{\partial d}{\partial b}\right|\cdot|\Delta b|+\left|\frac{\partial d}{\partial c_w}\right|\cdot|\Delta c_w|+\left|\frac{\partial d}{\partial \tau_{1b}}\right|\cdot|\Delta\tau|+\left|\frac{\partial d}{\partial \tau_{1s}}\right|\cdot|\Delta\tau|. \tag{14}$$

The error estimation is shown in Fig. 3 for depths of 1, 4, and 8 m of the calling animal. Both upper bounds depend on the position on the dolphin relative to the receiving hydrophone. The upper bound of the relative distance measurement error $\Delta r/r$ decreases with increasing distance and becomes almost constant with distances r larger than 25 m. The absolute depth error Δd has a minimum at distances between 5 and 20 m and then rises constantly with increasing dis-

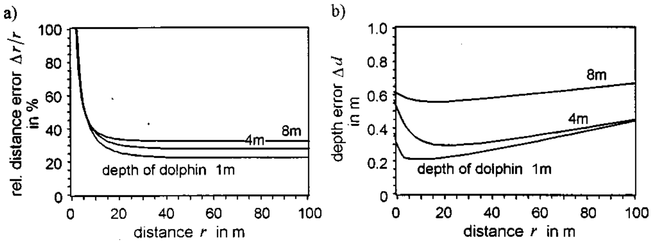

FIG. 3. (a) Relative error in distance measurement $\Delta r/r$ and (b) absolute depth error Δd of the localization.

tance. It is important to point out that these error estimates always give upper bounds. In practice, the actual localization errors are smaller since the measurement errors are typically normally distributed about the zero mean and tend to average out.

IV. RESULTS AND APPLICATIONS

The most interesting application of this localization method is the determination of source levels (SL) of click trains produced by cetaceans in the wild. This parameter is very important for studies of social behavior and foraging of these animals since it determines the range extent for communication and echolocation. Most source level measurements of dolphin echolocation clicks have been done with captive animals and may not necessarily reflect source levels produced by animals in open waters (Au, 1993). The broadband nature of social signals, particularly of the burst pulse signals of certain dolphin species, has been documented only recently, so that little or almost nothing is known about source levels of these signal types (Lammers *et al.*, 1998).

Since dolphins emit click sound directionally and the orientation of an animal cannot be determined with the method presented here, statements about the maximum source level of signals are only hypothetical. Source level is defined as the sound pressure level at 1 m from the source. It is often not measured at that distance so that the transmission loss due to spherical spreading and absorption must be taken into account with the equation

$$\mathrm{SL} = \mathrm{SPL}_R + 20 \cdot \log r + \alpha \cdot r, \tag{15}$$

where SPL_R is the sound pressure level *re* 1 μPa of the recorded signal, r is the distance between the dolphin and the hydrophone, and α is the absorption coefficient of the water measured in dB/m.

Maximum source levels of echolocation and burst pulse signals were determined for spinner dolphins at our study site. Only click trains of more than 10 clicks and at least 500-ms duration were examined. The maximum source levels were found for click trains where the position of the dolphin could be tracked over some distance and the animal's range continuously declined by 1 m/s or more. It was assumed that the dolphins orientated toward the hydrophone. A maximum peak-to-peak SL of 219 dB *re* 1 μPa was found for echolocation clicks and 214 dB *re* 1 μPa for burst pulse clicks of spinner dolphins, respectively. The upper bound of the distance measurement of $\Delta r/r < 0.35$ for distances $r > 20$ m translates into a source level measurement error ΔSL of

$$|\Delta \mathrm{SL}| = 20 \cdot \log\left(1 \pm \frac{\Delta r}{r}\right) \leqslant 3.7 \text{ dB}. \tag{16}$$

We assumed uncertainty involved with calculating the absorption coefficient does not contribute significantly to the source level measurement [α changes less than 0.02 dB/m for a water temperature change of 10 °C in the frequency range up to 200 kHz (Au, 1993)].

A second application of the presented localization method is the acoustic tracking of dolphins. Figure 4 shows a track of a spinner dolphin recorded along the Waianae coast of Oahu, Hawaii (near Kahe point). Each cross represents a calculated position derived from an echolocation click. The track covers 3 sec in time and a path length of about 6 m. During this time span the dolphin continuously emitted echolocation clicks with durations less than 50 μs and bandwidths exceeding that of our recording system (130 kHz). The interclick interval in this click train varied from 70 to 115 ms. As predicted from the error estimation, the deviation in depth is significantly lower than the deviation in the estimated distance.

About 10% of all the recorded echolocation and burst pulse sounds had two or more distinct signal reflections caused from multipath propagation and high enough signal-to-noise ratios for acoustic localization. Another 25% of the signals had overlapping components caused by propagating along a similar path length. In these cases analysis of the time delay and phase of the signal is uncertain. The range of localized animals was between 20 and 110 m, with signals from remote animals frequently containing three or more signal reflections that allowed the verification of the localization and error correction.

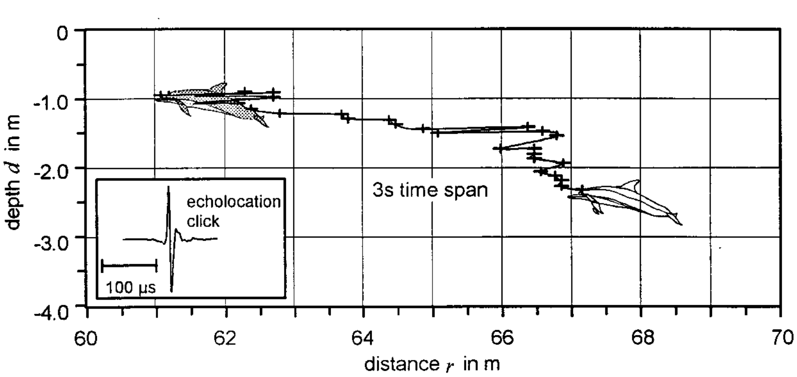

FIG. 4. Acoustic track of a Spinner dolphin at the Waianae coast of Oahu, Hawaii, and echolocation click of the dolphin. The fluctuations of the estimated positions (+) are due to the measurement errors.

V. CONCLUSIONS

The use of multipath propagation of cetacean click sound emissions for acoustic tracking with only one hydrophone provides a simple way to acquire valuable information about sound source levels and animal range and depth for wild dolphins. The technique requires almost no additional costs beyond a single channel recording system. Echolocation and burst pulse click trains allow precise measurements of time-of-arrival differences and the reliable identification of reflections paths by the evaluation of phase relations. The method provides higher two-dimensional (2D) localization (distance, depth) accuracy over large distances than visual range estimates and allows relatively precise estimates of sound source levels. Certain properties of the study site may limit the use of the localization method, since signal propagation over surface and bottom paths is absolutely required. In particular, the sea floor must be relatively even and of relatively high reflectivity (i.e., rock or sand). Signal overlap can complicate the arrival time measurements, so that localization is only possible for certain positions of the animal relative to the receiving hydrophone where surface and bottom reflection paths have distinctly different lengths. In addition, the animal must be oriented somewhat toward the hydrophone since the transmitting beam pattern of the animal is relatively narrow and signals at wide angles from the major axis of the beam can be attenuated significantly. The best results were achieved with animals close to the water surface and ranges considerably larger than the water depth.

In the past, repetitions of dolphin signals with time intervals of less than 1 ms been interpreted as double or multiple clicking by the animal (Norris, 1968). This paper suggests in some cases double clicks may be due to some surface reflection, that signal repetitions of spinner dolphins are, in fact, multipath propagation of single clicks emitted by the dolphin.

ACKNOWLEDGMENTS

This work was generously supported by research grants provided by the German Research Foundation (DFG) and by the Office of Naval Research (ONR). At the same time, the authors would like to extend their appreciation to Dr. Paul Nachtigall, director of the Marine Mammal Research Program, Hawaii Institute of Marine Biology, for his abundant support and encouragement.

Au, W. W. L. (**1980**). ''Echolocation signals of the Atlantic bottlenose dolphin (Tursiops truncatus) in open water,'' in *Animal Sonar Systems*, edited by R. G. Busnel and J. F. Fish (Plenum, New York), pp. 251–282.

Au, W. W. L. (**1993**). *The Sonar of Dolphins* (Springer, New York).

Au, W. W. L., Lammers, M. O., and Aubauer, R. (**1999**). ''A portable broadband data acquisition system for field studies in bioacoustics,'' Mar. Mammal Sci. **15**(2), 526–531.

Bronstein, I. N., and Semendjajew, K. A. (**1983**). *Taschenbuch der Mathematik* (Nauka, Moskau & Teubner, Leibzig), pp. 100, 276–277.

Cato, D. H. (**1998**). ''Simple methods of estimating source levels and locations of marine animal sounds,'' J. Acoust. Soc. Am. **104**(3), 1667–1678.

Clay, S. C., and Medwin, H. (**1977**). *Acoustical Oceanography: Principles and Applications* (Wiley, New York), pp. 3–11.

Lammers, M. O., Au, W. W. L., and Aubauer, R. (**1998**). ''The broadband nature of spinner dolphin (*Stenella longirostris*) social signals: Evidence from field studies,'' Abstracts of the 12th Biannual Conference on the Biology of Marine Mammals in Monaco, January (**1998**).

Norris, K. S. (**1968**). ''The echolocation of marine mammals,'' in *The Biology of Marine Mammals*, edited by T. H. Anderson (Academic, New York), pp. 391–423.

Spiesberger, J. L., and Fristrup, K. M. (**1990**). ''Passive localization of calling animals and sensing of their acoustic environment using acoustic tomography,'' Am. Nat. **135**, No. 1, 107–153.

Stephens, R. W. B. (**1970**). *Underwater Acoustics* (Wiley-Interscience, London), pp. 140–141.