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Tracking sperm whale (*Physeter macrocephalus*) dive profiles using a towed passive acoustic array[a]

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A passive acoustic method is presented for tracking sperm whale dive profiles, using two or three hydrophones deployed as either a vertical or large-aperture towed array. The relative arrival times between the direct and surface-reflected acoustic paths are used to obtain the ranges and depths of animals with respect to the array, provided that the hydrophone depths are independently measured. Besides reducing the number of hydrophones required, exploiting surface reflections simplifies automation of the data processing. Experimental results are shown from 2002 and 2003 cruises in the Gulf of Mexico for two different towed array deployments. The 2002 deployment consisted of two short-aperture towed arrays separated by 170 m, while the 2003 deployment placed an autonomous acoustic recorder in tandem with a short-aperture towed array, and used ship noise to time-align the acoustic data. The resulting dive profiles were independently checked using single-hydrophone localizations, whenever multipath reflections from the ocean bottom could be exploited to effectively create a large-aperture vertical array. This technique may have applications for basic research and for real-time mitigation for seismic airgun surveys. [DOI: 10.1121/1.1758972]

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I. INTRODUCTION

Sperm whales (*Physeter macrocephalus*) were the first large cetaceans to be associated with a distinctive underwater sound, particularly a 6–10-ms impulsive sound described as a click.[1–4] Decades of additional research have revealed that sperm whales are among the most acoustically active cetaceans. Over the course of a typical dive, which can last longer than 45 min, an individual animal can produce thousands of clicks.[5–10] A considerable body of knowledge has accumulated about these sounds, including statistics on their time-frequency characteristics,[5] repetition rates,[9] possible correlations between animal size and click structure,[11,12] and the identification of regional differences between acoustic repertoires.[13–15]

The rich acoustic lives of sperm whales have made passive acoustic monitoring a fundamental tool for researching their behavior, as well as for designing mitigation protocols to protect them from potentially harmful anthropogenic activities. One standard configuration involves deploying two towed hydrophones behind a monitoring vessel, with the hydrophones separated by a few meters. By measuring the relative arrival times of impulsive sounds on the hydrophones, the animal's bearing relative to the monitoring vessel can be determined, subject to a left–right ambiguity. Small aperture towed-array systems have proven successful in mapping sperm whale population distributions,[16–18] and automated detection bearing estimation software has been developed for public use.[19,20] There are circumstances, however, when more precise estimates of an animal's position are desirable. These situations include mitigation monitoring, when it is important to establish whether an animal is in an "exclusion zone," or to determine what sound characteristics an animal is being exposed to. For deep-diving animals such as sperm whales, depth may have to be solved simultaneously with range, to avoid inaccurate range estimates. While some proposed techniques use signal amplitude to estimate range,[21] this approach is problematic for sperm whales, whose sound source levels, even from a single individual, are highly variable.[22,23] Furthermore, evidence is accumulating that sperm whale sounds are highly directional,[23–25] and so the received signal amplitude of a sperm whale sound may vary with an animal's orientation relative to the hydrophone, as well as range. Therefore a single small-aperture array configuration is generally insufficient for range and depth tracking.

If additional hydrophones are deployed, separated by large baselines, the position of a whale within the volume in the vicinity of the deployment can be tracked by measuring the relative arrival times of all direct-path signals across the hydrophones. Both bottom-mounted[26] and portable configurations[27–30] of this type exist. Deploying such a distributed system to observe a mobile group of animals can be logistically difficult. For example, sperm whales typically move at horizontal speeds of up to 3 knots (1.5 m/s) relative to local currents in the Gulf of Mexico and other regions.[31]

Multipath reflections of underwater biological sounds can be used to reduce the number of physical hydrophones required to acquire a position.[32,33] The surface-reflected path, or surface "ghost" of a click, has been used to track sperm whales from a vertical array,[34] as well as a horizontal array when a depth-recording tag has been attached to an animal.[35]

[a]Section II of this work was briefly presented in "Passive three-dimensional tracking of sperm whales using two towed arrays during the 2001 SWAMP cruise," by A.M. Thode, David K Mellinger, and Anthony Martinez, at Cancun, Mexico, 144th ASA Conference, December 2002. However, the data in this work have never been presented.

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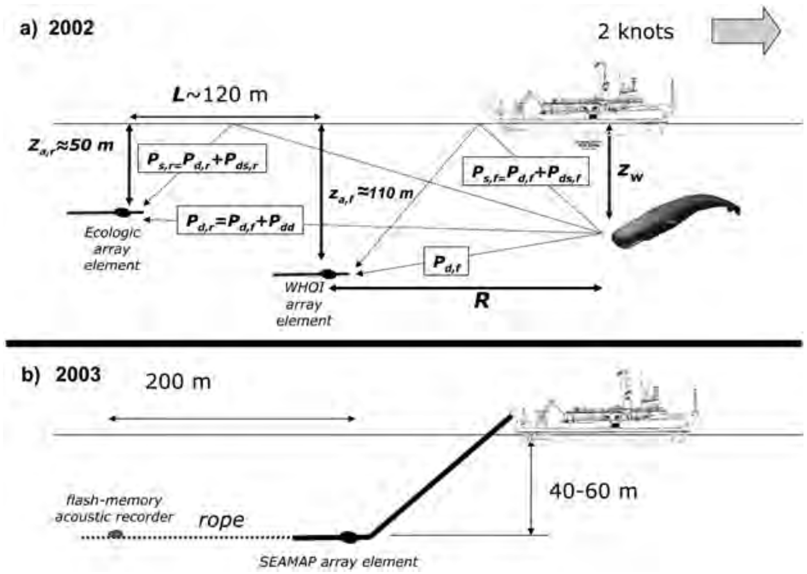

FIG. 1. Deployment geometries of towed passive acoustic range-depth tracking system, illustrating acoustic propagation paths used in the tracking: (a) 2002 configuration, consisting of two short-aperture towed arrays, with the forward (f) array deployed to a depth of around 110 m, and the rear (r) array to a depth of about 50 m. Tow cables are not shown for clarity. (b) 2003 configuration. An autonomous acoustic recorder is attached to a 5/8 in polypropylene rope, the end of which is attached to a towed acoustic array manufactured by SEAMAP, Inc. Only a single element of the short-aperture arrays is displayed for clarity.

Bottom-reflected paths have also been used to obtain dive profiles of sperm whales using a single hydrophone;[25] however, bottom-arrivals are often not available, are difficult to detect with automated software whenever they are present, and are difficult to associate with a particular direct arrival whenever more than one animal is acoustically active.

This paper presents a two-hydrophone tracking technique for obtaining low-resolution dive tracks of multiple animals simultaneously, provided that the hydrophone depths are measured independently. Such techniques are already being explored theoretically.[36] The hydrophones can be deployed as either a vertical array or a wide-aperture towed array, but all experimental work to date has been performed on a towed configuration. By exploiting surface-reflected sounds, a virtual planar array can be created that can track animals out to 1 km horizontal range, for hydrophone separations on the order of 200 m. The surface-reflections have been observed even when the ocean surface is agitated.

The computations required by the method lend themselves to automation, and have been tested on two separate sperm whale research cruises in the Gulf of Mexico in 2002 and 2003, as part of a larger research consortium called the Sperm Whale Seismic Study (SWSS), supported jointly by the Minerals Management Service (MMS), the Industry Research Funders Coalition (a coalition of oil and gas and geophysical survey companies), the Office of Naval Research (ONR), and the National Science Foundation (NSF).

In this paper, Sec. II discusses the basic tracking concept, including assumptions and limitations, while Sec. III details the practical implementation of the method, including deployment geometries and automated signal processing techniques. Finally, Sec. IV presents the results from two different towed array deployments in 2002 and 2003.

II. THEORY

A. Notation

The basic tracking geometry is illustrated in Fig. 1 for two possible towed configurations. Two hydrophones, labeled "forward" and "rear," are deployed at respective depths $z_{a,f}$ and $z_{a,r}$. A whale at horizontal range R_f from the forward hydrophone and depth z_w makes an impulsive sound that travels a distance (slant range) $P_{d,f}$ before being recorded by the forward hydrophone as a "direct" path. A "surface-reflected" path $P_{s,f}$ also exists, arriving at a time $t_{ds,f}=P_{ds,f}/c$ after the direct path arrival, where $P_{ds,f}=(P_{s,f}-P_{d,f})$ is the path-length difference, and c is the effective speed of sound in water. It is assumed here that c is constant with depth, so that all sound propagation paths can be represented by straight lines. Even in the Gulf of Mexico, where the sound speed is a strong function of depth, a previous analysis[25] found that at ranges less than 1 km, ray refraction effects could be neglected, a conclusion shared by other work.[37]

The sound also travels a distance $P_{d,r}=(P_{d,f}+P_{dd})$ before being recorded on the rear hydrophone, where P_{dd} is the path difference between the direct arrivals on both hydrophones. An additional surface-reflected path arrives at the rear hydrophone at a time $t_{ds,r}$ after the direct arrival. The times $t_{ds,f}$, $t_{ds,r}$, and $t_{dd}=P_{dd}/c$ are the measurable quantities from the hydrophone data, as illustrated in Fig. 2. Thus a relationship between these times and the whale's range and depth is required.

B. Derivation of tracking formulas

For each hydrophone the slant range $P_{d,i}$ and surface-reflected path length $P_{s,i}$ can be expressed as

$$P_{d,i}=\sqrt{R_i^2+(z_w-z_{a,i})^2},$$
$$P_{s,i}=\sqrt{R_i^2+(z_w+z_{a,i})^2}, \tag{1}$$

where the subscript i represents either the forward (f) or rear (r) hydrophone. Squaring the two expressions, then subtracting from each other yields

$$4z_{a,i}z_w=P_{s,i}^2-P_{d,i}^2=c^2t_{ds,i}(2t_{d,i}+t_{ds,i}). \tag{2}$$

Dividing Eq. (2) for the forward phone by the equation for the rear phone and substituting for $t_{d,r}$ yields

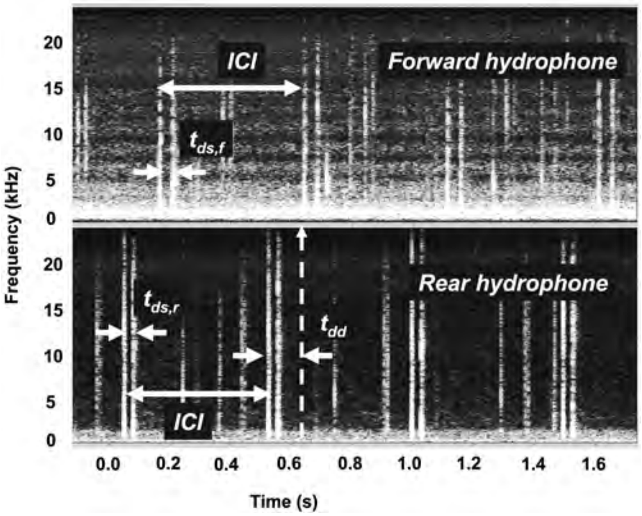

FIG. 2. A spectrogram display illustrating the measurements required for range-depth tracking, taken from data collected during 2002 (48 kHz sample rate, 1024 pt. FFT samples, 75% overlap). The top spectrogram display shows data from the forward hydrophone, and the bottom display shows a simultaneous recording from the rear hydrophone. Three pieces of information can be obtained from each click an individual makes: the differences between the arrival times of the direct and surface-reflected paths on the forward ($t_{ds,f}$) and rear ($t_{ds,r}$) hydrophones, and the arrival time difference between the direct arrivals on both hydrophones (t_{dd}). Also shown is the inter-click interval (ICI), which is used to identify the same whale on both hydrophones.

$$\frac{z_{a,f}}{z_{a,r}}=\frac{t_{ds,f}(2t_{d,f}+t_{ds,f})}{t_{ds,r}(2t_{d,f}+2t_{dd}+t_{ds,r})}. \tag{3}$$

The left-hand side of Eq. (3) is the ratio between the two hydrophone depths. Therefore, if the hydrophone depths are independently measured, the slant range $P_{d,f}$ can be determined:

$$P_{d,f}=c\,\frac{t_{ds,f}-(t_{ds,r}+2t_{dd})S}{2(S-1)},\qquad S=(t_{ds,r}z_{a,f}/t_{ds,f}z_{a,r}). \tag{4}$$

The whale depth and range can then be obtained from Eqs. (2) and (1), respectively. Note that if ray refraction effects are negligible, knowledge of the horizontal separation L between the two hydrophones is not required to obtain a range-depth dive profile. However, to obtain a full three-dimensional fix, including azimuth, the horizontal separation must be estimated. Equations (1)–(4) are equally valid for a wide-aperture vertical array deployment.

The "stability factor" S in Eq. (4) determines the stability of Eq. (4); the closer S is to one, the more precise the measurements of $P_{ds,i}$ and the array depths need to be to obtain a precise answer. A binomial expansion of Eq. (1), assuming $R_i \gg z_{a,i}+z_w$, produces $ct_{ds,i}\approx R_i+(z_w+z_{a,i})^2/2R_i-R_i-(z_w-z_{a,i})^2/2R_i=2z_w z_{a,i}/R_i$, which reduces the stability factor in Eq. (4) to $S\approx R_f/R_r$. Therefore at large ranges S tends to be greater than one if the animal is behind the towed array, less than one if the animal is ahead of the array, and close to one when the animal is broadside of the hydrophones, i.e., when t_{dd} is nearly zero. At large ranges the stability factor can be physically interpreted as a crude measure of whale azimuth.

Equation (4) thus indicates that the tracking procedure is least accurate whenever the hydrophones are shallow and the animal is nearly equidistant from both hydrophones, with horizontal ranges greater than roughly five times the mean hydrophone depths. By contrast, the procedure is most stable whenever the animals are directly ahead or behind the towing vessel, the hydrophones are relatively deep, and the animal range is less than a few hydrophone depths. However, at close ranges some locations slightly forward or aft of broadside may still yield unstable tracks, depending on the relative hydrophone depths.

Occasionally faint bottom-reflected paths can be detected in the acoustic data. If the water depth is known, this additional arrival time information can yield a range and depth from a single hydrophone,[25] providing an independent check of the procedure presented here.

III. EXPERIMENTAL SETUP

This section discusses the practicalities of deploying a towed array configuration sufficient for tracking animals out to 1–2 km horizontal range, as well as the signal-processing techniques required to automatically extract estimates of P_{dd}, $t_{ds,f}$, and $t_{ds,r}$ in Fig. 2.

A. Array deployments

In order to use Eq. (4) effectively, a practical towed array deployment needs the following characteristics:

(1) Two hydrophones spaced at least 200 m apart permit stable tracking of animals up to a range of 1–2 km. Ideally, one of the locations contains a level short-aperture towed array, to estimate whale azimuth along with the dive profile.
(2) Two hydrophones placed at least 30 m deep to obtain relatively large values of P_{ds}. Consequently arrays should be towed at 3 knots (about 1.5 m/s) or less, unless the hydrophone cable can be attached to a dive wing.
(3) Hydrophone depths recorded accurately and continuously. The deeper the array, the less precise the measurement needs to be, but an accuracy of at least 1 m is recommended.

Two deployment geometries meeting these criteria were tested during separate SWSS research cruises in the Gulf of Mexico during 2002 and 2003.

1. 2002 deployment

On 5 September 2002, a feasibility test was conducted in the Gulf of Mexico off the R/V *Gyre*, owned by Texas A&M University. The data were collected during weather conditions that were too rough to permit other activities associated with the SWSS project.

Two arrays were deployed simultaneously off the port and starboard sides of the stern, as illustrated in Fig. 1(a). The port array, which consisted of three elements spaced over 3 m, was built by the Woods Hole Oceanographic Institution (WHOI). A dive wing was used to keep the hydrophones at depths greater than 100 m, while maintaining a 20-m horizontal separation between the forward hydrophone and ship stern. A calibrated pressure transducer was attached to the top of the dive wing, and a LED display permitted notes to be taken of the transducer depth over time. Unfortunately, this sensor failed during the experiment, so the WHOI array depth had to be estimated, based on earlier measurements, as a function of ship speed through the water.

The starboard array, a two-element oil-filled array built by Ecologic Inc., was deployed approximately 300 m behind the stern. This created a horizontal separation of 170 m between the forward (WHOI) and rear (Ecologic) hydrophone. A Suunto Vyper dive computer was attached to the head of the array, which logged the array hydrophone depth every 10 s. Typical recorded depths for this configuration were between 40 and 60 m. For this array data from only one array element were available.

The acoustic data from both arrays were sampled at 48 kHz and recorded simultaneously to hard disk and tape for later analysis. Unfortunately, while bottom-reflected paths could be identified in the acoustic record, the number of whales present made assignment of a particular bottom echo to a particular direct arrival difficult.

2. 2003 deployment and data preprocessing

During May and June of 2003 the deployment illustrated in Fig. 1(b) was attempted from the R/V *Ewing*, operated by the Lamont-Doherty Earth Observatory for the National Science Foundation (NSF). Instead of deploying two separate array cables, a single array, manufactured by SEAMAP Inc., was deployed roughly 300 m behind the stern. The array had four hydrophones unevenly spaced over a span of 50 m, each of which sampled at 48 kHz. Depth data were measured by a pressure transducer embedded in the array, which were converted into a data string that could be sampled over a serial port by a laptop. During the times to be discussed here, the array depth varied between 37 and 50 m.

An autonomous flash-memory acoustic recorder,[38] built by Bill Burgess of Greeneridge Sciences Inc., was taped to 261 m of a 16-mm ($\frac{5}{8}$ in.) polypropylene rope. A 7-kg shackle that served as an end anchor was tied to one rope end, while the other was attached to the end of the array. The recorder had a pressure transducer to log a time-stamped depth, which varied between 42 and 62 m over the results presented here. It also had 1 Gbyte of flash memory, sufficient to record at 8.192 kHz for nearly 17 h. In order to retrieve the data the entire assembly had to be retrieved from the water.

The acoustic data on the recorder was time-aligned with the data of the leading array element by cross-correlating the ship engine noise recorded on both hydrophones. First, both time series were interpolated and decimated to produce two time series sampled at 8 kHz. Next, a digital high-pass filter was applied to both time series to emphasize frequencies above 500 Hz. Although ship noise was present at lower frequencies, flow noise on the autonomous recorder dominated the lower frequency bands, decorrelating the data. As the hydrophone depths and the length of the rope between the recorder and array were already known, the time lag expected from the cross-correlation between a hydrophone on the SEAMAP array and the autonomous recorder could be estimated, and the acoustic data were subsequently time-aligned. The autonomous recorder clock drift relative to the most forward array element was not linear, but experienced sudden clock jumps about once an hour, which seemed to correspond to large changes in ship course and speed. These jumps were corrected before further analysis.

Neither the rope deployment nor the attachment of the autonomous recorder to the rope was very sophisticated. As a result, flow noise was extensive, and the hydrophone physically fluttered in the current, resulting in the acoustic data from the autonomous recorder being clipped between 50 to 600 times per second. Fortunately, since sperm whale sounds are impulsive, the subsequent signal processing could still extract useful information.

3. General tracking procedure

The basic tracking procedure for both deployments was similar. The experiments were conducted in the evening, while other sperm whale research activities were suspended, and the passive acoustic monitoring team had full control of the vessel. The acoustic operator tried to maneuver the vessel so that a group of animals was forward and to one side of the vessel. The ship speed through the water was then reduced to a minimum possible speed that still permitted steerage—typically around 2 knots (1 m/s). The ship maintained a steady heading as the vessel gradually overtook and passed a set of animals, who moved horizontally at speeds of about 2–3 knots (1–1.5 m/s), relative to the current. The distance of the vessel from the animals was adjusted so that surface reflections were visible on the spectrogram monitoring display (e.g., Fig. 2). After a complete pass, the vessel increased speed, turned away from the group, circled around, and attempted another pass. Attempts were made to avoid approaching the animals too closely, but as the subsequent tracking results show, the ship did pass over an animal at depth.

B. Signal processing and estimate extraction

An advantage of using surface-reflected paths for tracking animals, besides reducing the number required hydrophones, is that it simplifies the signal processing. In this section the methods for extracting estimates for $t_{ds,f}$, $t_{ds,r}$, and t_{dd} are presented, assuming that any needed preprocessing, such as time-synchronization, has already been performed on the forward and rear time-series.

The first step in tracking a group of animals is to analyze the acoustic data using a pulse detection program, such as Ishmael,[39] that outputs a set of times at which the spectral power over a certain bandwidth exceeds a threshold value. For the higher-bandwidth towed array this detection bandwidth was set between 4 and 15 kHz, while for the autonomous recorder the detection bandwidth was set between 2 and 3 kHz, which still provided sub-millisecond time resolution. The set of possible click detections for a given hydrophone is designated t_{pulse}, and t^i_{pulse} is the ith detection of that set.

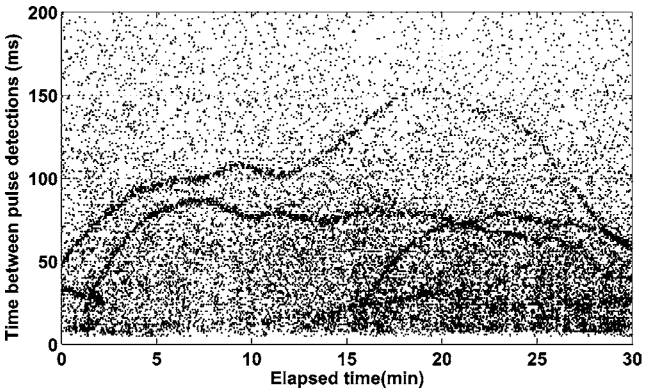

FIG. 3. Demonstration of how individual whales can be separately identified on a single hydrophone by estimating t_{ds}, using data beginning at 5 September 2002, 22:15 CDT, on the forward hydrophone element. Because different whales generally have different t_{ds} values at a particular moment, up to four whales can be identified simultaneously from a single time series.

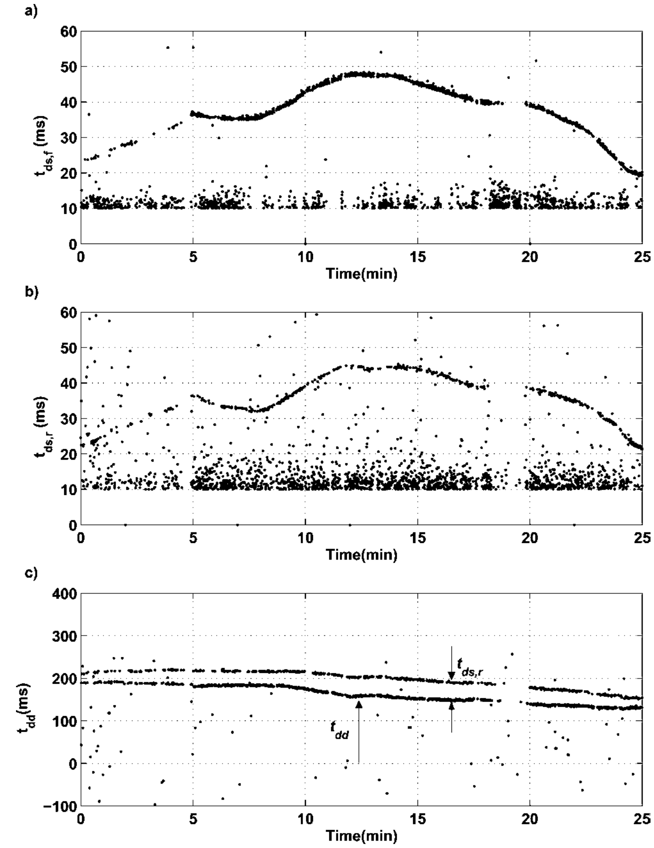

FIG. 4. Example of automated estimates of (a) $t_{ds,f}$ (b) $t_{ds,r}$ and (c) t_{dd}, using data from 19 June 2003, starting at 00:20 CDT. Cepstral analysis was used to estimate (a) and (b), while a "rhythm analysis" that compared sets of nine ICI sequences between hydrophones was used to derive (c). Note the presence of an additional "ghost" curve in (c), which represents the arrival time difference between the surface reflection on the rear phone and the direct arrival on the forward phone. Thus the difference between the two curves provides an alternate means for computing $t_{ds,r}$.

The next step involves distinguishing a set of direct arrivals from one individual from surface reflections and direct arrivals from other animals. There are two ways to do this. If the forward hydrophone location actually contains two hydrophones separated by a few meters, as was the case in 2003, then the direct arrivals from different animals can be isolated by plotting the estimated bearing of detected pulses versus time. Bearings from surface reflections can be distinguished from those of direct arrivals because the apparent arrival angles of the surface reflections vary greatly over a short period of time (a high variance in estimated array bearing), while the bearings from direct paths have little variance over a short time period.

If data are available from only a single hydrophone at the rear location, as was the case in 2002 with the Ecologic array, then the direct arrivals can still be identified by plotting the time difference between sequential detections, $t_{pulse}^{i+1} - t_{pulse}^{i}$, as a function of time (Fig. 3). The most likely pulse to arrive after a true direct arrival is the associated surface reflection, unless a direct arrival from a different individual arrives first. As the time separation $t_{ds,f}$ is generally less than 50 ms, the likelihood of a direct arrival from another individual falling within this interval is relatively small, as long as four animals or less are present. Plotting the time differences is thus a crude way of estimating $t_{ds,f}$ from a single hydrophone. Since no two whales generally share the same $t_{ds,f}$ value at a given moment, multiple animals can often be separated within a single time series.

Once the direct arrivals are identified, a more precise estimate of $t_{ds,f}$ often can be obtained using cepstral analysis,[35,40,41] a coherent deconvolution technique that works well if the surface-reflected signal can be modeled as a broadband-filtered version of the direct arrival. During the mild summer conditions in the Gulf of Mexico, the ocean surface was smooth enough that these conditions were usually met for the forward and rear hydrophone data, as illustrated in Figs. 4(a) and 4(b), respectively, using 2003 data.

The time delay between front and rear hydrophones, t_{dd}, is then obtained by exploiting the fact that the interval between subsequent clicks by the same animal, or the "interclick interval" (ICI), must be the same at both hydrophone locations (see Fig. 2). A routine can be written where the N ICIs following a given direct-path arrival at the forward location are compared with a set of candidate pulses at the rear location. All candidate pulses lie within a time L/c of the original direct-path arrival at the forward location. For each candidate pulse, the routine checks whether N additional pulses are present at the rear location during future times required by the ICIs, to within a 1 ms tolerance. The candidate pulse that shares the most ICIs is selected as the corresponding direct arrival for the rear hydrophone location. This software "rhythm analysis" technique, illustrated in Fig. 4(c), has been extensively used in automated marine mammal monitoring at various Naval Test ranges,[42,43] where it is informally called a "scanning sieve."

An interesting side effect of the rhythm analysis is that the surface reflection associated with the rear hydrophone often emerges as a secondary choice in the output [Fig. 4(c)]. In other words, the analysis often identifies the arrival time difference between the surface reflection on the rear hydrophone location and the direct arrival on the forward hydrophone. From the definition of t_{dd} it is apparent that the surface-reflected "ghost" t_{dd} is always more positive than the actual t_{dd}. The time difference between the two curves thus provides an alternate means of computing $t_{ds,r}$. This

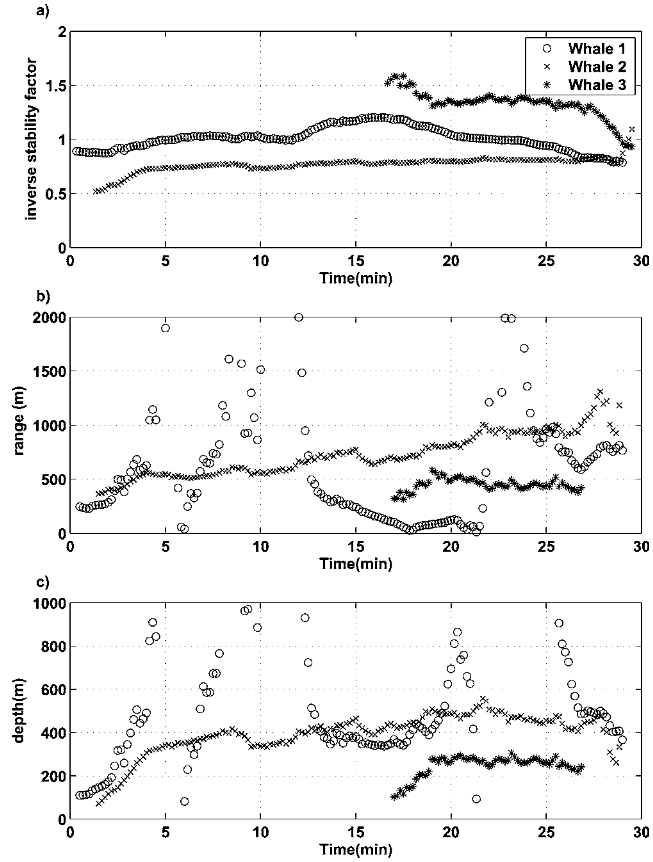

FIG. 5. Range-depth track estimate of three whales, using data beginning at 5 September 2002, 22:15 CDT, covering the same time period as Fig. 3. For each whale track the inverse stability factor ($1/S$) of Eq. (4) is shown in (a), the horizontal ranges from the forward hydrophone are shown in (b), and the whale depths are shown in (c). Note the instability of the track estimate whenever $S \sim 1$. The animals seem to be diving to depths between 300 and 500 m.

technique was useful in the 2003 experiment, when clipping and flow noise on the autonomous recorder often precluded cepstral analysis and other coherent techniques [the time period shown in Fig. 4(b) being an exception].

Once a display like Fig. 4 is obtained, a final step involves tracing the curves for the three time quantities, interpolating the samples into evenly spaced time samples, then inserting the values into Eqs. (1)–(4). Although this tracing process can be automated,[35] the results presented here were obtained by manually selecting the tracks using a graphical user interface.

IV. RESULTS

A. 2002 configuration

In 2002 4 h of data were collected on 5 September to test the tracking procedure. Figure 5 shows the 30-min period during that experiment, beginning at 22:15 CDT, when three whales were clearly identified using the single-hydrophone method discussed in Sec. III B, and illustrated in Fig. 3. During this period the ship made two port turns of 45 and 30 degrees at 2 and 8 min, respectively. The ship's course paralleled the whales', because the relative bearings changed only gradually with time, except during the ship turns. Figure 5 plots the inverse stability factor $1/S$, the horizontal range from the forward hydrophone R_f, and the depth for each whale. The inverse stability factor is shown so that an animal forward of the vessel displays a larger positive value on the graph.

The track for whale 1 illustrates how the procedure becomes inaccurate whenever the stability factor wanders close to 1. Initially whale 1 was on the port side of the vessel, slightly aft of the array. After the ship made its first port turn, the apparent position of whale 1 shifted broadside to the array, so that $1/S$ became one, t_{dd} became close to zero, and tracking became unstable. After the second port turn the towed array shifted again at 11 min, the apparent position of the whale shifted forward of the array, the inverse stability factor increased to 1.25 at 15 min, and stable depths and ranges were reacquired. Whale 1 passed in front of the vessel at 18 min, and eventually the ship passed the whale. At 21 min the whale became broadside to the array again, $1/S$ falls past one, and the track was lost.

By contrast whale 2 always remained roughly aft of the array, while whale 3 was forward of the array for most of the sequence. Thus the inversion results for these animals always remained stable. Initial descents and presumed foraging depths between 200 and 400 m can be observed for both whales. When stable depth estimates are available for whale 1, they are comparable to the whale 2 depth of roughly 400 m.

Unfortunately, independent checks of the dive profiles derived here were not possible. Bottom-reflected arrivals, although present, were fleeting and could not be matched with their corresponding direct arrivals with confidence, due to the number of animals present. None of the animals were tagged at this time, but some indirect comparisons can be made with time/depth data from animals tagged during the same cruise.[44] The estimated initial descent rates of whales 2 and 3 are 1.6 and 1.22 m/s, respectively. The estimated depths at the end of the initial descents of whales 2 and 3 in Fig. 5 were 390 and 270 m, respectively, and maximum estimated depths attained by all three animals were 490, 500, and 280 m, respectively.

A tag deployed on an animal from the same group the following morning (JD 249a) measured two complete dive cycles, with mean descent rates of 1.17 ± 0.17 m/s, close to the average rate of 1.15 ± 0.14 m/s estimated from whales tagged in the Gulf of Mexico and the Mediterranean.[45] The initial steep descents ended at depths of 508 and 528 m, but during presumed foraging the whale reached maximum depths of 650 and 690 m. The results from 64 dives from all 13 animals tagged during the 2002 cruise had initial descent depths ranging between 400 and 800 m, with the mode at 500 m, and maximum dive depths ranging between 475 and 850 m, with a peak clustered between 600 and 700 m.[46] The estimated descent rates roughly correspond to those derived from all tag data, as well as from whale 249a only. However, the initial and maximum dive depths estimated from the passive acoustic measurements for whales 1 and 2 are on the extreme lower end of the 2002 tag dive depth distributions, and 100 m shallower than the maximum dive depths of whale 249a. The depths of whale 3 are nearly 200 m shallower than those of whales 1 and 2, and thus are incompat-

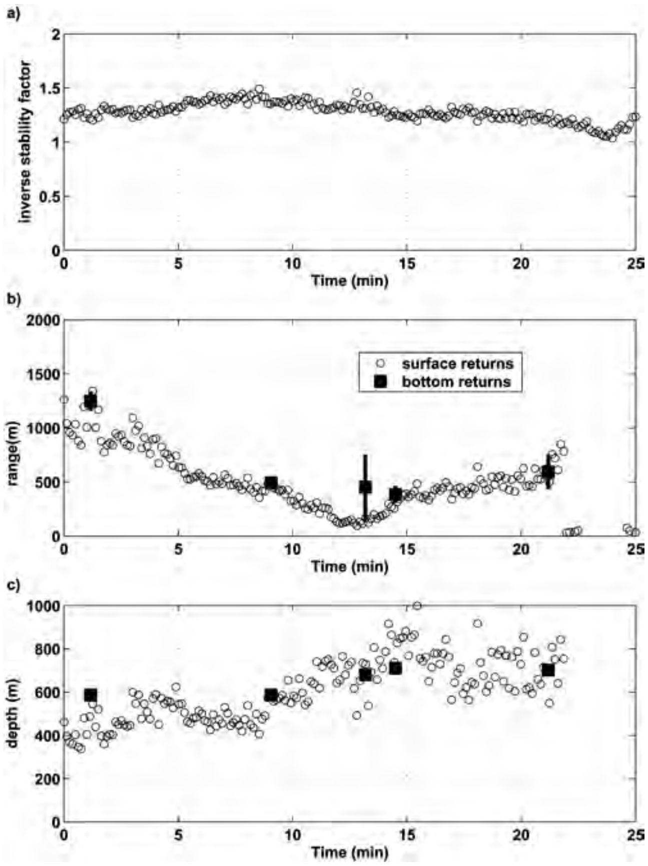

FIG. 6. Track of whale using autonomous recorder data starting at 19 June 2003, 00:20 CDT. (a) Inverse stability factor; (b) range from forward hydrophone; and (c) depth. The black squares mark independent localization estimates opportunistically obtained by exploiting bottom-reflected acoustic paths. Black bars on squares represent one standard deviation of the estimates derived from bottom arrivals over a 20-s interval.

ible with any of the tag dive profiles. It is impossible to tell, from the 2002 data, whether these depth discrepancies are due to incorrect estimates of the towed array depths, or reflect actual differences in diving behavior when animals are in close proximity to the ship. Additional measurements with simultaneous independent location estimates were a high priority for 2003.

B. 2003 configuration

From the evening of 18 June through the early morning of 19 June 2003, the autonomous recorder configuration shown in Fig. 1(b) was used to collect additional data to test the procedure. One particularly clear set of time measurements was available between 00:20 and 00:45 CDT, and is displayed in Fig. 4. The dive profile derived from Fig. 4 is shown in Fig. 6. The inverse stability factor plot in Fig. 6(a) indicates that the animal remained forward of the rear hydrophone location, although the close proximity of the animal precludes a simple interpretation of the stability factor. The majority of the animal's depths vary between 400 and 800 m—deeper than depths estimated in 2002. The plot of horizontal range from the forward hydrophone indicates that the array passed directly over the animal approximately 12 to 15 min into the sequence.

Sets of bottom-reflected arrivals were recorded on the array several times during this sequence, and by manual observation of spectrogram displays they could be matched to the corresponding direct-path arrivals, since only two animals were acoustically active during this time. Occasional estimates of the whale position could then be made using only a single hydrophone,[25] by measuring sets of bottom arrivals over a 20-s interval. The array depth estimated from this procedure matched the measured depth of the SEAMAP array to within a few meters. The mean and standard deviations of the positions obtained from each set of bottom arrivals are marked as black squares and vertical lines in Figs. 6(b) and 6(c). They overlap the positions estimated by the two-hydrophone method to within the standard deviation.

V. CONCLUSION

A two-hydrophone passive acoustic method for tracking sperm whale dive profiles has been presented, for the particular configuration of a wide-aperture towed array. By taking advantage of surface-reflected paths, which occur over 90% of the time when the array is less than 2 km range from the animal, this approach simplifies the signal processing required to extract the relative arrival time information needed for tracking. The algorithm has been tested using data collected during 2002 and 2003 in the Gulf of Mexico, and in 2003 the results were independently checked using additional information provided by bottom-reflected paths. While the focus of the work has been on sperm whales, any impulsive biological sound could be tracked using the same principles discussed here,[47] provided that the directivity of the signals is not so great that surface multipath arrival amplitudes are reduced below background noise levels. Given the broadband nature of most biological pulses, and the size of most deep-diving marine mammals, it seems reasonable that some portion of the lower end of the pulse's acoustic spectrum would be nearly omnidirectional. Low source signal amplitudes and surface roughness are currently expected to be the limiting restrictions on the approach discussed here, especially for any vertical or towed array deployment deeper than 100 m.

To date all configurations tested have used two to three towed hydrophones spaced less than 300 m apart, restricting the usable horizontal tracking range of less than 2 km. Other configurations are possible, including a vertical array, and even towed array configurations of greater aperture. However, at some range beyond 1 km the approximation of a uniform water-column sound speed becomes increasingly inaccurate and ray refraction effects would have to be explicitly incorporated into the procedure. Another uncertainty about the procedure is under what weather conditions the surface roughness would increase to the point where coherent-processing techniques, such as cepstral analysis, could no longer be applied to surface-reflected signals, and less-precise incoherent methods, such as the "rhythm analysis" presented in Sec. III B, would have to be employed instead. While a more quantitative error analysis for this technique is desirable, preliminary modeling by the author and modeling work by other researchers (e.g., Ref. 37) has suggested that "measurement errors" in terms of imprecise estimation of relative time-of-arrivals dominate "model-based errors" arising from neglecting ray-refraction effects, for the tracking ranges and depths discussed in this paper.

A final question concerning this procedure is how closely an observational vessel can approach a group of animals without provoking deviations in their natural dive behavior. This issue is of concern to any cetacean research experiment that attempts to measure possible responses of marine mammals to various types of anthropogenic noise. It is hoped that further development of this method can help provide insight into what "stand-off" distances should be observed in open-ocean marine mammal research.

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