The effect of recording and analysis bandwidth on acoustic identification of delphinid species

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Because many cetacean species produce characteristic calls that propagate well under water, acoustic techniques can be used to detect and identify them. The ability to identify cetaceans to species using acoustic methods varies and may be affected by recording and analysis bandwidth. To examine the effect of bandwidth on species identification, whistles were recorded from four delphinid species (*Delphinus delphis*, *Stenella attenuata, S. coeruleoalba*, and *S. longirostris*) in the eastern tropical Pacific ocean. Four spectrograms, each with a different upper frequency limit (20, 24, 30, and 40 kHz), were created for each whistle ($n=484$). Eight variables (beginning, ending, minimum, and maximum frequency; duration; number of inflection points; number of steps; and presence/absence of harmonics) were measured from the fundamental frequency of each whistle. The whistle repertoires of all four species contained fundamental frequencies extending above 20 kHz. Overall correct classification using discriminant function analysis ranged from 30% for the 20-kHz upper frequency limit data to 37% for the 40-kHz upper frequency limit data. For the four species included in this study, an upper bandwidth limit of at least 24 kHz is required for an accurate representation of fundamental whistle contours.
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I. INTRODUCTION

Shipboard cetacean abundance surveys have traditionally relied on visual line transect methods (Holt, 1987; Wade and Gerrodette, 1993; Barlow, 1995; Jaramillo-Legorreta *et al.*, 1999; Carretta *et al.*, 2000; Jefferson, 2000; Buckland *et al.*, 2001; Hammond *et al.*, 2002). Visual detection and identification of cetaceans can be challenging as these animals spend most of their lives completely under water. Many cetacean species produce characteristic calls that propagate well under water (Richardson *et al.*, 1995), and therefore acoustic techniques can be used to detect and identify them. Because of this, towed hydrophone arrays are becoming increasingly common elements of cetacean abundance surveys (Thomas *et al.*, 1986; Leaper *et al.*, 1992; Clark and Fristrup, 1997; Goold 1998; Norris *et al.*, 1999; Gordon *et al.*, 2000; Oswald *et al.*, 2003).

The ability to identify cetaceans to species using acoustic methods varies. Many large whales, including blue whales [*Balaenoptera musculus* (Thompson *et al.*, 1996; Stafford *et al.*, 1999)], fin whales [*Balaenoptera physalus* (Thompson *et al.*, 1992)], and sperm whales [*Physeter macrocephalus* (Weilgart and Whitehead, 1993; Goold and Jones, 1995)], produce stereotyped calls that are easily recognized. The calls produced by many dolphin species are more variable, making acoustic identification of these species difficult (Oswald *et al.*, 2003).

Time and frequency characteristics measured from spectrograms have been used to classify delphinid whistles to species in several studies (Steiner, 1981; Wang *et al.*, 1995; Matthews *et al.*, 1999; Rendell *et al.*, 1999; Oswald *et al.*, 2003). These studies have had varying degrees of success, ranging from 28% correct classification of ten species (Matthews *et al.*, 1999) to 70% correct classification of five species (Steiner, 1981). These correct classification scores are significantly higher than expected by chance, but are lower than the usual standards applied to visual identification during shipboard surveys (i.e., near certainty).

The bandwidth with which sounds are recorded and analyzed may have an effect on the ability to classify them to species. Analysis bandwidths vary among studies and are not always reported. Steiner (1981) reported an analysis bandwidth of 0–32 kHz, Wang *et al.* (1995) an analysis bandwidth of 0–25 kHz, and Oswald *et al.* (2003) an analysis bandwidth of 20 Hz to 20 kHz. These bandwidths may not be sufficient to provide complete, accurate representations of vocal repertoires because ultrasonic frequencies (above 20 kHz) are produced by many odontocete species. Whistles with fundamental frequencies extending into the ultrasonic range have been reported for several delphinid species, including spinner dolphins (*Stenella longirostris*) and Atlantic spotted dolphins [*S. frontalis* (Lammers *et al.*, 1997, 2003)], and white-beaked dolphins [*Lagenorhynchus albirostris* (Rasmussen and Miller, 2002)]. Thus, classification errors may be due to inaccurate whistle measurements resulting from bandwidth limitations.

The objectives of this study are twofold: (1) to evaluate the extent to which four delphinid species recorded in the eastern tropical Pacific ocean produce whistles with funda-

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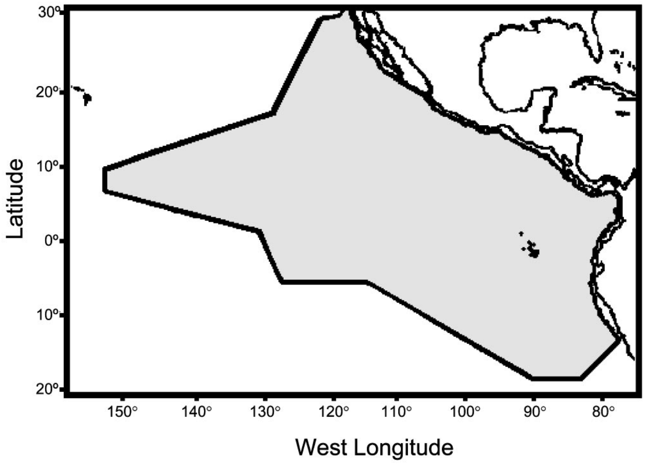

FIG. 1. Eastern tropical Pacific ocean study area for ''*Stenella* Abundance Research'' (STAR2000) survey.

mental frequencies extending into the ultrasonic range, and (2) to examine the effect of increasing bandwidth on acoustic species identification.

II. METHODOLOGY

Recordings were made during the ''*Stenella* Abundance Research'' (STAR2000) survey conducted in the eastern tropical Pacific ocean from 28 July to 9 December 2000. The study area extended from the United States/Mexico border southward to the territorial waters of Peru, and from the continental shores of the Americas to the longitude of Hawaii (Fig. 1). Visual line-transect methods were used to survey all cetaceans encountered in the study area (Kinzey *et al.*, 2001).

A hydrophone array was towed at a depth of 4-6 m approximately 200 m behind the NOAA ship *McArthur* while traveling at a survey speed of 10 kt. The depth of the array was periodically monitored using a *Suunto Solution Nitrox* dive computer. Two calibrated arrays were used during the survey: (1) a five-element array (flat frequency response ± 4 dB from 2 to 45 kHz at -132 dB *re* 1v/μPa after internal amplification), and (2) a three-element array (flat frequency response ± 3 dB from 2 to 120 kHz at -164 dB *re* 1v/μPa after internal amplification). The three-element array was used during 2 of the 29 recording sessions that were included in the analysis. A total of 17 whistles from these two encounters were included in the analysis (versus 467 whistles from 27 recording sessions using the five-element array). Any differences in sensitivity between the two arrays are therefore not likely to have had a significant effect on the results. Also, the selection of whistles was based on a signal-to-noise ratio, which did not differ between the two arrays. An acoustic technician monitored signals from two hydrophones in the array using a stereo headset and custom-written software that displayed real-time scrolling spectrograms. Recordings were made using custom software that recorded signals directly to computer hard drive via an analog-to-digital conversion card (*Data Translation DT-3809*). Recordings were made using sampling rates between 100 and 200 kilo-samples/second. Anti-aliasing filters were applied prior to recording.

Based on sample sizes of acoustic recordings made during the survey, whistles of four delphinid species were chosen for analysis: short-beaked common dolphins, *Delphinus delphis*; pantropical spotted dolphins, *Stenella attenuata*; striped dolphins, *S. coeruleoalba*; and spinner dolphins. Only recordings of groups that had been visually identified to species and observed to contain only one species were included in the analysis. Because it is possible that some recordings identified as ''single species'' may contain faint vocalizations produced by other species in the area, only ''loud and clear'' whistles were analyzed. Whistles were considered to be ''loud and clear'' if they were at least 9 dB louder than background noise.

Richardson *et al.* (1995) suggest that the maximum detection range for many delphinid species is on the order of 1 km. To be conservative, we assumed that whistles detected within 3 km of the array would be of sufficient quality for analysis. To avoid including whistles produced by dolphins other than those being observed and recorded, recordings made within 3 km of any other delphinid groups were excluded from the analysis. Distance was calculated between the location of the ship at the beginning of the recording session in question and the location of the initial sighting of the next group of dolphins encountered (based on angle and reticle measurements read from binoculars). Distance was also calculated between the location of the ship at the beginning of the recording session in question and the location of the previous group of dolphins encountered when they were last seen. Any recording session that occurred within 3 km of either the next or previous sighting was excluded from the analysis.

Fifty percent of the loud and clear whistles recorded during each acoustic encounter were randomly selected for analysis, up to a maximum of 30 whistles per encounter. It

TABLE I. Number of recording sessions and number of whistles included in the analysis (n) for each species. Percentages of whistles containing at least one off-scale variable when measured with an upper bandwidth limit of 20, 24, 30, and 40 kHz are given in the last four columns.

Species	No. of recording sessions	n	20 kHz	24 kHz	30 kHz	40 kHz
Short-beaked common dolphin	11	163	28%	8%	1%	0%
Spotted dolphin	5	100	43%	9%	3%	0%
Striped dolphin	9	104	11%	0%	0%	0%
Spinner dolphin	4	117	27%	4%	0%	0%

TABLE II. Descriptive statistics (means, with standard deviations in parentheses underneath) for measured whistle variables. Maximum frequency and ending frequency increased significantly with increasing upper bandwidth limit for all species except striped dolphins (one-way ANOVA, $\alpha = 0.05$). Significant P-values are underlined.

Species	Upper bandwidth limit (kHz)	Beginning frequency (kHz)	Ending frequency (kHz)	Minimum frequency (kHz)	Maximum frequency (kHz)	Duration (s)	No. of inflection points	No. of steps
Short-beaked common dolphin	20	11.8	12.4	8.7	15.4	0.68	1.7	1.2
		(3.8)	(4.8)	(2.3)	(2.7)	(0.43)	(1.5)	(1.6)
	24	12.3	13.8	8.7	16.7	0.70	1.8	1.2
		(4.3)	(4.8)	(2.3)	(3.5)	(0.42)	(1.5)	(1.7)
	30	12.6	14.1	8.6	17.5	0.75	1.8	1.2
		(4.7)	(5.4)	(2.3)	(4.4)	(0.44)	(1.5)	(1.8)
	40	12.9	14.1	8.6	17.7	0.75	1.8	1.2
		(5.2)	(5.4)	(2.3)	(4.6)	(0.44)	(1.5)	(1.7)
	P	0.31	0.003	0.99	<0.001	0.55	0.84	0.93
Spotted dolphin	20	10.3	13.9	9.0	16.0	0.56	1.1	2.3
		(4.4)	(4.9)	(3.9)	(3.6)	(0.42)	(1.9)	(2.6)
	24	10.4	15.6	9.0	18.4	0.60	1.2	2.7
		(4.5)	(5.1)	(3.9)	(4.1)	(0.40)	(1.8)	(3.3)
	30	10.4	16.1	9.0	18.9	0.62	1.2	2.8
		(4.5)	(5.6)	(3.9)	(4.4)	(0.40)	(1.8)	(3.4)
	40	10.4	16.8	9.0	19.4	0.63	1.2	2.8
		(4.5)	(6.4)	(3.9)	(5.2)	(0.40)	(1.8)	(3.4)
	P	0.99	0.01	1.0	<0.001	0.59	0.86	0.77
Striped dolphin	20	10.4	12.5	8.6	15.1	0.61	1.6	1.6
		(3.4)	(3.9)	(2.1)	(2.5)	(0.36)	(1.8)	(2.0)
	24	10.6	12.8	8.5	15.9	0.64	1.7	1.7
		(3.8)	(3.5)	(2.1)	(3.3)	(0.37)	(1.8)	(2.1)
	30	10.6	12.8	8.5	15.9	0.64	1.7	1.7
		(3.8)	(3.5)	(2.1)	(3.3)	(0.37)	(1.8)	(2.1)
	40	10.6	12.8	8.5	15.9	0.64	1.7	1.7
		(3.8)	(3.5)	(2.1)	(3.3)	(0.37)	(1.8)	(2.1)
	P	0.97	0.70	0.99	0.17	0.92	0.96	0.94
Spinner dolphin	20	12.8	13.0	10.8	15.8	0.55	1.8	0.87
		(3.9)	(4.9)	(3.1)	(3.1)	(0.46)	(3.8)	(1.5)
	24	13.5	14.6	11.1	17.4	0.66	2.0	0.98
		(4.5)	(4.7)	(3.7)	(4.0)	(0.49)	(3.8)	(1.7)
	30	13.7	15.0	11.1	17.8	0.67	2.0	0.98
		(4.7)	(5.1)	(3.7)	(4.4)	(0.49)	(3.8)	(1.7)
	40	13.7	15.0	11.1	17.8	0.67	2.0	0.98
		(4.7)	(5.1)	(3.7)	(4.4)	(0.49)	(3.8)	(1.7)
	P	0.52	0.003	0.87	0.001	0.26	0.73	0.99

was assumed that this degree of subsampling would allow a sufficient sample size to be obtained while minimizing the risk of over-sampling groups or individuals (which can lead to non-independence of data). Overlapping whistles were only included in the data set if each individual whistle contour could be discerned without question.

Four spectrograms (512-point FFT), each with a different upper frequency limit (20, 24, 30, and 40 kHz), were created for each whistle using commercially available sound analysis software, ‘‘*SpectraPlus*.’’ Eight variables were measured from the fundamental frequency of each whistle: (1) beginning frequency (Hz), (2) ending frequency (Hz), (3) minimum frequency (Hz), (4) maximum frequency (Hz), (5) duration (ms), (6) number of inflection points (defined as a change from positive to negative or negative to positive slope), (7) number of steps (defined as a sudden jump in frequency over a short time period), and (8) presence/absence of harmonics (a binary variable).

Following Oswald *et al.* (2003), multivariate discriminant function analysis (DFA) was used to classify whistles to species based on spectrographic measurements. Prior to running DFA, continuous variables (frequency variables, duration, and number of steps and inflection points) were tested for normality and were square-root or log transformed as necessary. The binary variable (presence/absence of harmonics) was coded as dummy variables. Discriminant function analysis classifies whistles to prespecified groups based on orthogonal linear functions derived from the measured variables. Some whistles were missing measurements for one or more variables because a portion of the whistle extended beyond the upper bandwidth limit. These whistles were excluded from the DFA, resulting in different sample sizes for the different upper bandwidth limit data sets.

A modified jackknife, or cross-validation, method was used to calculate correct classification scores for DFAs. Each recording session was omitted from the total sample and new

TABLE III. Classification results of discriminant function analysis for the 20-kHz upper bandwidth limit data. Percentages of whistles correctly classified for each species are in bold. Correct classification scores that are significantly different (χ^2 test, $\alpha = 0.05$) than expected by chance alone are underlined and P-values are given in the sixth column. The number of whistles included in the analysis for each species (n) is given in the last column. Overall, 30% of whistles were classified to the correct species. This is significantly greater ($P = 0.02$) than the 25% that would be expected by chance alone.

	Predicted species					
Actual species	Short-beaked common dolphin	Spotted dolphin	Striped dolphin	Spinner dolphin	P	n
Short-beaked common dolphin	**37%**	16%	20%	27%	0.003	118
Spotted dolphin	21%	**23%**	32%	24%	0.76	56
Striped dolphin	24%	32%	**16%**	28%	0.05	93
Spinner dolphin	19%	18%	21%	**42%**	<0.001	85

discriminant functions were calculated for classification of the omitted whistles. The discriminant functions calculated using this method were therefore created from data independent of the whistles being classified. This helped ensure that whistles were classified based on species-specific characteristics rather than group- or individual-specific characteristics. To evaluate correct classification scores, it is necessary to compare them to what would be expected by chance alone. Chi-square was used to test whether correct classification was significantly greater than expected by chance alone. Statistical significance was evaluated at $\alpha = 0.05$ without corrections for multiple testing.

III. RESULTS

A total of 484 whistles from 29 different recording sessions were included in the analysis (Table I). Some whistle variables could not be determined if a portion of the fundamental frequency of the whistle extended beyond the upper limit of the analysis bandwidth. These variables were labeled as "off-scale" variables. The percent of whistles with off-scale variables ranged from 11% for striped dolphins to 43% for spotted dolphins when the upper bandwidth limit was 20 kHz (Table I). When the upper bandwidth limit was increased to 24 kHz, the percent of whistles with at least one off-scale variable decreased for every species, ranging from 0% for striped dolphins to 9% for spotted dolphins. An additional 6 kHz increase in upper bandwidth limit reduced the percent of whistles with off-scale variables even further. No whistles had off-scale variables when the upper bandwidth limit was 40 kHz.

Descriptive statistics (means and standard deviations) for all bandwidth limit data are given in Table II. Only maximum and ending frequency showed significant differences with increasing upper bandwidth limit (one-way ANOVA, $\alpha = 0.05$). Maximum and ending frequency increased significantly with increasing upper bandwidth limit in all species except striped dolphins.

Results of the DFAs are given in Tables III–VI. For all bandwidths, both overall percent correct classification (30%–37%) and percent correct classification of spinner dolphin whistles (37%–42%) were significantly greater than the 25% expected by chance alone (χ^2 tests; overall, $P < 0.05$; spinner dolphins, $P < 0.003$). When the upper bandwidth limit was 20 kHz, percent correct classification was not significantly different than chance for spotted dolphins (23%, χ^2 test, $P = 0.76$) and was significantly less than chance for striped dolphins (16%, χ^2 test, $P = 0.05$). For both species, percent correct classification increased to significantly greater than chance when the upper bandwidth limit was increased to 24 kHz (χ^2 tests; spotted dolphins, 40%, $P = 0.002$; striped dolphins, 36%, $P = 0.01$), and remained significantly greater than chance at all subsequent bandwidths. In contrast, the percent of short-beaked common dolphin whistles that were correctly classified was significantly greater than chance (37%, χ^2 test, $P = 0.003$) when the upper

TABLE IV. Classification results of discriminant function analysis for the 24-kHz upper bandwidth limit data. Percentages of whistles correctly classified for each species are in bold. Correct classification scores that are significantly different (χ^2 test, $\alpha = 0.05$) than expected by chance alone are underlined and P-values are given in the sixth column. The number of whistles included in the analysis for each species (n) is given in the last column. Overall, 37% of whistles were classified to the correct species. This is significantly greater ($P < 0.001$) than the 25% that would be expected by chance alone.

	Predicted species					
Actual species	Short-beaked common dolphin	Spotted dolphin	Striped dolphin	Spinner dolphin	P	n
Short-beaked common dolphin	**32%**	19%	30%	19%	0.06	150
Spotted dolphin	15%	**40%**	25%	20%	0.002	91
Striped dolphin	22%	23%	**36%**	19%	0.01	104
Spinner dolphin	19%	15%	24%	**42%**	<0.001	112

TABLE V. Classification results of discriminant function analysis for the 30-kHz upper bandwidth limit data. Percentages of whistles correctly classified for each species are in bold. Correct classification scores that are significantly different (χ^2 test, $\alpha = 0.05$) than expected by chance alone are underlined and P-values are given in the sixth column. The number of whistles included in the analysis for each species (n) is given in the last column. Overall, 36% of whistles were classified to the correct species. This is significantly greater ($P < 0.001$) than the 25% that would be expected by chance alone.

	Predicted species					
Actual species	Short-beaked common dolphin	Spotted dolphin	Striped dolphin	Spinner dolphin	P	n
Short-beaked common dolphin	**29%**	20%	31%	20%	0.27	161
Spotted dolphin	13%	**42%**	25%	20%	<0.001	96
Striped dolphin	19%	21%	**40%**	20%	<0.001	104
Spinner dolphin	21%	15%	27%	**37%**	0.003	117

bandwidth limit was 20 kHz and decreased to not significantly different than chance when the upper bandwidth limit was increased to 24 kHz (32%, χ^2 test, $P = 0.06$), 30 kHz (29%, χ^2 test, $P = 0.27$), and 40 kHz (30%, χ^2 test, $P = 0.21$).

IV. DISCUSSION

The production of clicks containing ultrasonic components is common in several dolphin species (Au, 1980; Kamminga and Wiersma, 1981; Wiersma, 1982; Dawson, 1991; Au, 1993; Lammers *et al.*, 2003), and delphinid whistles often have harmonic components that extend well above 20 kHz (Lammers *et al.*, 2003). In contrast, the production of whistles with fundamental frequencies extending into the ultrasonic range has been documented for few species (Lammers *et al.*, 1997; Au *et al.*, 1999; Rasmussen and Miller, 2002; Lammers *et al.*, 2003). The whistle repertoires of all four species examined in this study contained whistles with fundamental frequencies extending into the ultrasonic range. While all species produced high-frequency whistles, some used high frequencies more often than others. For example, 43% of spotted dolphin whistles had fundamental frequencies that extended beyond 20 kHz, compared to only 11% of striped dolphin whistles (Table I).

The presence of whistles with fundamental frequencies extending beyond the upper limit of the analysis bandwidth can lead to inaccurate representations of whistle contours and have an adverse effect on the ability to classify whistles to species. For example, the spotted dolphin whistle shown in Fig. 2 has an ending frequency of 39 kHz. When this whistle was analyzed using an upper bandwidth limit of less than 40 kHz, it was impossible to determine not only ending frequency, but also maximum frequency and whistle duration. This whistle also has harmonics that were completely missed when the upper bandwidth limit was less than 30 kHz.

In addition to this loss of information, the presence of off-scale variables can lead to misrepresentations of whistles. The fundamental contour of the striped dolphin whistle shown in Fig. 3 appears to be entirely below 20 kHz when the upper bandwidth limit is 20 kHz [Fig. 3(a)]. When the upper bandwidth limit is increased to 24 kHz it becomes apparent that this contour does contain energy above 20 kHz [Fig. 3(b)]. For this whistle, duration, beginning frequency, and maximum frequency were all underestimated when the upper bandwidth limit was 20 kHz. This whistle also has a harmonic component that was missed when the upper bandwidth limit was 20 kHz.

Overall, for the species in this study, loss of information and misrepresentation had the greatest effect on measurements of maximum and ending frequency. Both variables increased significantly with increasing upper bandwidth limit for every species except striped dolphins (Table II).

Increased accuracy of whistle measurements resulting from increasing bandwidth led to greater overall success in acoustic species identification. Overall correct classification increased from 30% to 37% when the upper bandwidth limit was increased from 20 to 24 kHz, and varied only slightly when bandwidth was increased further (Tables III–VI). More substantial increases were evident in some individual species percent correct classification scores. Percent correct classification of spotted and striped dolphin whistles increased from not significantly different than chance (spotted dolphins) or significantly less than chance (striped dolphins) to significantly greater than chance when the upper bandwidth limit was increased from 20 to 24 kHz. Classification success for both species increased further with subsequent increases in bandwidth, but the most sizeable increases occurred between 20 and 24 kHz.

In contrast, percent correct classification of short-beaked common and spinner dolphin whistles decreased as bandwidth increased. Even with these decreases, classification success for spinner dolphin whistles remained significantly greater than chance at all bandwidths. Percent correct classification of short-beaked common dolphin whistles decreased from significantly greater than chance at 20 kHz upper bandwidth limit to not significantly different than chance at all other upper bandwidth limits. This was an unexpected result as both species had a relatively high percentage of off-scale whistles when the upper bandwidth limit was 20 kHz and relatively low percentages of off-scale whistles at higher upper bandwidth limits. Also, average maximum frequency and average ending frequency increased significantly with increasing bandwidth for both species.

Fewer off-scale whistles and more accurate whistle measurements should lead to more complete representations of whistles at higher upper bandwidth limits. It was expected

TABLE VI. Classification results of discriminant function analysis for the 40-kHz upper bandwidth limit data. Percentages of whistles correctly classified for each species are in bold. Correct classification scores that are significantly different (χ^2 test, $\alpha = 0.05$) than expected by chance alone are underlined and P-values are given in the sixth column. The number of whistles included in the analysis for each species (n) is given in the last column. Overall, 37% of whistles were classified to the correct species. This is significantly greater ($P < 0.001$) than the 25% that would be expected by chance alone.

	Predicted species					
Actual species	Short-beaked common dolphin	Spotted dolphin	Striped dolphin	Spinner dolphin	P	n
Short-beaked common dolphin	**30%**	20%	31%	19%	0.21	163
Spotted dolphin	13%	**44%**	23%	20%	<0.001	100
Striped dolphin	19%	19%	**42%**	20%	<0.001	104
Spinner dolphin	20%	16%	26%	**38%**	0.001	117

that this would lead to greater classification success, but as illustrated in the cases of short-beaked common and spinner dolphins, this was not always true. In addition, striped dolphins had the lowest percentage of off-scale whistles when the upper bandwidth limit was 20 kHz and their whistle variables did not change significantly with increasing bandwidth, yet striped dolphin correct classification scores increased markedly with increasing bandwidth. Thus, classification success was not directly related to the percentage of off-scale whistles or changes in mean whistle variables with increasing bandwidth.

To further explore trends in classification success, patterns of misclassification were examined. When the upper bandwidth limit was increased from 20 to 24 kHz, the percent of short-beaked common dolphin whistles that were correctly classified decreased. At the same time, the percent of short-beaked common dolphin whistles that were misclassified as striped dolphins increased (Tables III and IV). It was hypothesized that the additional whistles being misclassified as striped dolphins by the 24-kHz upper bandwidth limit DFA were those that had been excluded from the 20-kHz upper bandwidth limit DFA (recall that whistles with off-scale variables were excluded from the DFA). This hypothesis was rejected because, of the 33 short-beaked common dolphin whistles that were missing from the 20-kHz upper bandwidth limit data set, only one was misclassified as a striped dolphin whistle when included in the 24-kHz upper bandwidth limit DFA. Many ($n = 15$) of the missing short-beaked common dolphin whistles were misclassified as spotted dolphins and one third were correctly classified. This suggests that the observed changes in patterns of classification were not caused directly by the added whistles, but were more likely caused indirectly by the influence of additional whistles on the calculation of discriminant functions. Discriminant functions are orthogonal linear functions derived from the measured variables and will be affected by the relationship of whistle variables to one another as well as the values of the whistle variables themselves. Consequently, when evaluating the benefits of increasing bandwidth, it is not sufficient to examine the percent of off-scale whistle variables or changes in whistle variables with changes in bandwidth for individual species. It is also necessary to consider the ways in which representations of whistles change in relation to whistles of other species.

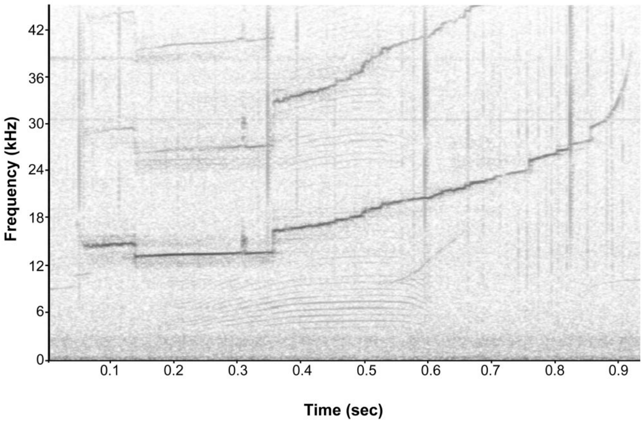

FIG. 2. Spotted dolphin whistle (512 point FFT). Maximum frequency, ending frequency, and duration were impossible to measure when the whistle was analyzed using an upper bandwidth limit less than 40 kHz. Harmonics were completely missed when the upper bandwidth limit was less than 30 kHz.

It is important to note that although percent correct classification of short-beaked common and spinner dolphin whistles did decrease with increasing bandwidth, the decreases (5% for spinner dolphins and 8% for short-beaked common dolphins) were minor compared to the 21% (spotted dolphin) and 26% (striped dolphin) increases in correct classification that were observed.

Even with sufficient bandwidth, classification success was lower than desirable for use as a field identification tool. Classification was based on eight variables that could be measured relatively easily and reliably in the field. These variables, however, do not provide complete representations of whistles and may miss whistle characteristics that carry species-specific information. Fristrup and Watkins (1993) measured variables such as amplitude, median frequency, and mode frequency (frequency corresponding to the largest energy value in the spectrum) from the vocalizations of 53 marine mammal species (including mysticetes, odontocetes, and pinnipeds). They devised a number of statistical measures to quantify the relationships among time, amplitude, and frequency. When tree-based classification models were applied to these variables, 66% of the vocalizations were classified to the correct species. Another approach to whistle

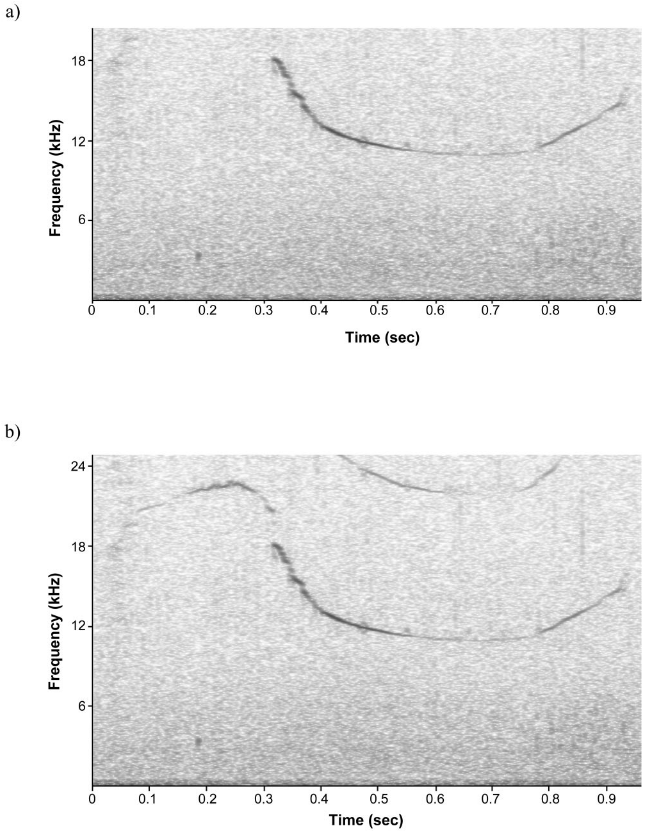

FIG. 3. Striped dolphin whistle (512 point FFT). (a) Upper bandwidth limit=20 kHz. (b) Upper bandwidth limit=24 kHz. Beginning frequency, maximum frequency, and duration were underestimated and harmonic was missed when the whistle was analyzed using an upper bandwidth limit less than 24 kHz.

classification was taken by Buck and Tyack (1993) and McCowan (1995). In these studies, overall whistle contours were compared rather than specific acoustic parameters. Different variables and approaches such as these could increase the accuracy of delphinid species identification.

Another cause of the lower than desirable correct classification scores could be that classification decisions were based on one whistle at time. This may be analogous to asking a visual observer to determine species from a single random surfacing of a single individual. Determining species based on several whistles may prove more reliable than classifying one whistle at a time.

The results of this study suggest that for the four species included, an upper bandwidth limit of at least 24 kHz is required for an accurate representation of the fundamental frequencies of their whistles and for optimizing the ability of computerized statistical techniques such as DFA to classify these whistles to species. The percentage of off-scale whistles, mean maximum and ending frequencies, and overall percent correct classification scores showed marked differences when the upper bandwidth limit was increased from 20 to 24 kHz. Increasing the upper bandwidth limit beyond 24 kHz did result in fewer off-scale whistles as well as changes in whistle variables and percent correct classification scores; however, these changes were minor compared to the changes occurring between 20 and 24 kHz.

Many acoustic research projects involve the use of DAT recorders, which typically have the capability to sample at either 44 100 or 48 000 kilo-samples/second. The results of this study suggest that the use of DAT recorders is sufficient for examinations of the fundamental frequencies of most dolphin whistles, however care should be taken to sample at 48 000 kilo-samples/second. If alternate equipment is available, advantages can be gained by recording and analyzing dolphin whistles at higher sampling rates.

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