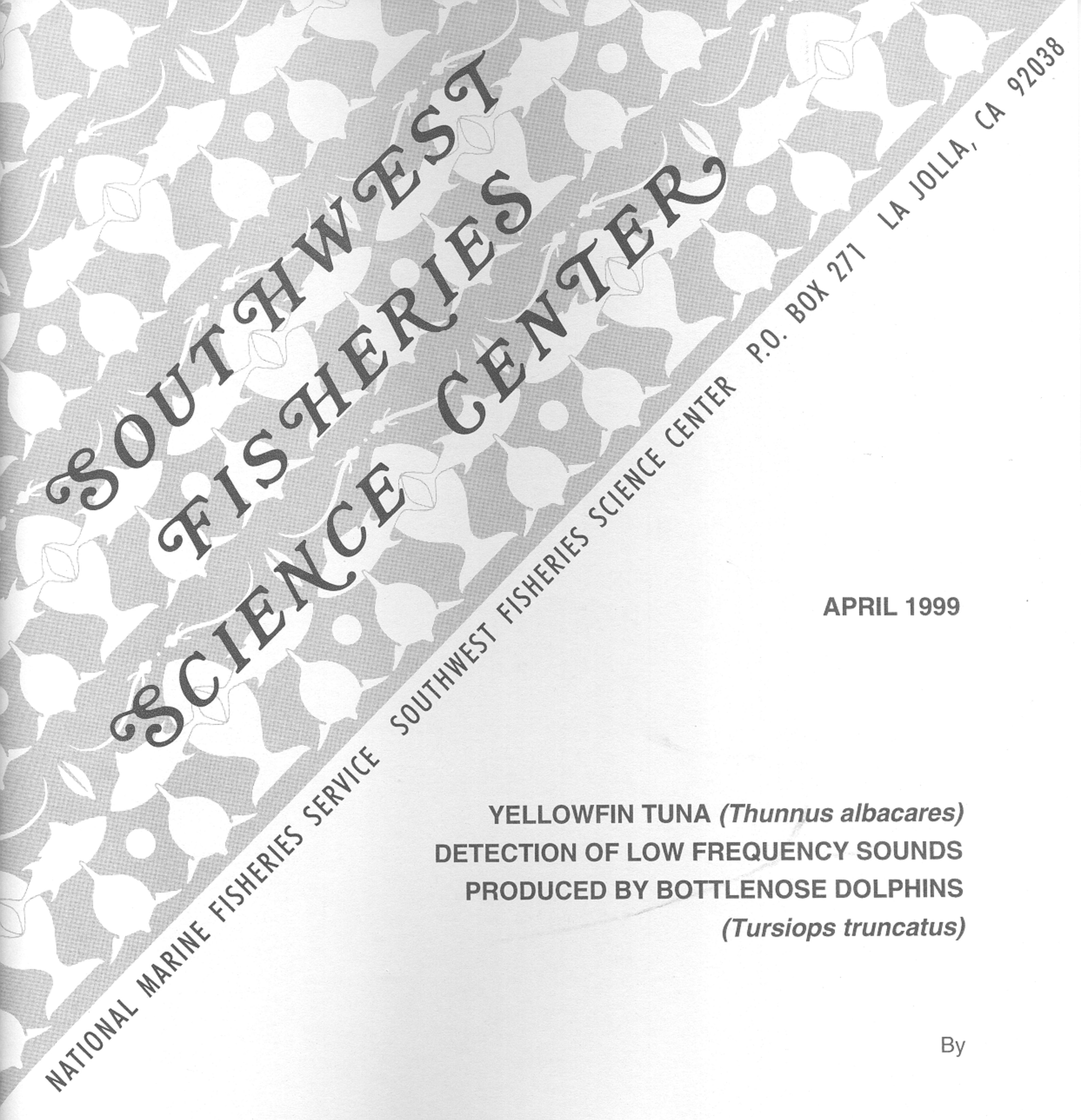

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YELLOWFIN TUNA *(Thunnus albacares)* DETECTION OF LOW FREQUENCY SOUNDS PRODUCED BY BOTTLENOSE DOLPHINS *(Tursiops truncatus)*

By

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Yellowfin tuna (*Thunnus albacares*) detection of low frequency sounds produced by bottlenose dolphins (*Tursiops truncatus*)

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EXPLANATORY NOTE

This report is one in a series on the potential for technology applications to enhance efficiency in commercial fisheries, reduce the catch of non-targeted species, and provide new tools for fishery assessments in support of the NMFS strategic goals to build sustainable fisheries and recover protected species. We hope the distribution of this report will facilitate further discussion and research into the application's potential usefulness, but should not be construed as an endorsement of the application by NMFS.

Pursuant to changes in the Marine Mammal Protection Act in 1988, the NMFS' SWFSC began another series of ETP-related studies in 1990, focused on developing and evaluating methods of capturing yellowfin tuna, which do not involve dolphins. This series of studies has been conducted within the SWFSC's Dolphin-Safe Research Program. Studies on the potential use of airborne lidar (LIght Detection And Ranging) systems began in 1991, and studies on low-frequency acoustic systems to detect fish schools at ranges much greater than currently possible were initiated during 1995. In addition to their use as an alternative to fishing on dolphins, these systems have potential to increase the efficiency of the fishing operations by locating fish schools not detectable by customary visual means, and as a fishery-independent tool to conduct population assessments on pelagic fish. They also have potential to adversely impact marine animals.

The Dolphin-Safe Research Program is investigating, through a series of contracts and grants, five airborne lidars: 1) the NMFS-developed “Osprey” lidar (Oliver et al. 1994), 2) the Kaman Aerospace Corporation's FISHEYE imaging lidar (Oliver and Edwards 1996), 3) the NOAA Environmental Technology Laboratory's Experimental Oceanographic Fisheries Lidar (Churnside et al. 1998), 4) the Arete Associates 3D Streak-Tube Imaging Lidar, and 5) the Detection Limited's lidar. An initial study on the potential effects of airborne lidars on marine mammals will be completed during 1998 (Zorn et al. 1998).

The Dolphin-Safe Research Program has completed, through a series of contracts and grants, acoustic system studies on 1) the acoustic target strength of large yellowfin tuna schools (Nero 1996), 2) acoustic detection parameters and potential in the eastern tropical Pacific Ocean (Rees 1996), 3) the design of two towed acoustic systems (Rees 1998, Denny et al. 1998), 4) measurements of swimbladder volumes from large yellowfin tuna (Schaefer and Oliver 1998) and, 5) the potential effects of low-frequency sound on marine mammals (Ketten 1998).

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Yellowfin tuna (*Thunnus albacares*) detection of low frequency sounds produced by bottlenose dolphins (*Tursiops truncatus*)

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ABSTRACT

In this study, source levels for some low-frequency sounds produced by bottlenose dolphins (*Tursiops truncatus*) were measured and used to estimate the maximum distance that these sounds could be detected by yellowfin tuna (*Thunnus albacares*). Three types of sounds were examined: an internally generated sound referred to as a jaw pop, and two sounds produced by dolphin's breaching and tail slap behaviors. Breaches and jaw pops produced the highest 1/3-octave source levels between 200–800 Hz (160 and 163 dB *re*: 1 µPa-m, respectively), which resulted in estimated maximum audible ranges between 850–900 m. The tail slaps were less intense (138 dB *re*: 1 µPa-m) and resulted in a maximum estimated detection range of approximately 90 m. These data are based on the lowest mean hearing threshold from two individual yellowfin (89 dB *re*: 1 µPa) [Iversen, R.T.B. (1967). "Response of the yellowfin tuna (*Thunnus albacares*) to underwater sound," in *Marine Bioacoustics*, Vol. 2, ed. W.N. Tavolga (Pergamon, Oxford)]. Using the lowest threshold from either fish (83 dB *re*: 1 µPa) results in a maximum estimated audible range of 1700–1800 m for the jaw pops and breaches.

INTRODUCTION

For over 50 years, tuna fishermen in the eastern Pacific Ocean (EPO) have exploited an association between a few species of dolphins (pantropical spotted dolphin, *Stenella attenuata*, spinner dolphin, *Stenella longirostris,* and short-beak common dolphin, *Delphinus delphis*), and yellowfin tuna, *Thunnus albacares*, to locate and capture the tuna (Perrin, 1968; Perrin 1969; National Research Council, 1992). Similar associations have been noted and exploited in other oceans, but the association is especially strong in the EPO. Improvements in purse seine equipment in the 1950's allowed fishermen to set their nets around herds of dolphins and capture the associated tuna, producing nearly one-fourth of the world's tuna catch. However, the practice also produced large numbers of dolphin mortalities and focused research on the fishing practice and dolphin populations. Although dolphin mortalities in this fishery have been significantly reduced through education, gear innovations, and quotas, the reason for the strong tuna/dolphin association in the EPO is still unclear (Edwards, 1992; Scott and Cattanach, 1998). Fishermen believe larger yellowfin tuna are attracted to the dolphins (National Research Council, 1992), which raises the question of how tuna detect dolphins. Schaefer and Oliver (1998) suggested yellowfin tuna could hear low-frequency sounds produced by dolphins and estimated a range of distances tuna could detect dolphins using maximum source levels reported for high-frequency dolphin sounds.

Dolphins are highly social animals and communicate with one another using a wide variety of whistles and pulse bursts (Popper, 1980). Dolphins also emit ultrasonic pulses while echolocating (Au, 1993). In addition to these sounds generated by the nasal system (Cranford *et al*., 1996; Ridgway *et al*., 1980), dolphins also produce sound through their interaction with the water: by swimming, jumping high in the air and landing on their sides or back (breaching), or striking the water's surface with their flukes (tail slaps) or head (head slaps) (Würsig and Würsig, 1980). The vast majority of fishes studied have been shown to have a relatively narrow audible frequency range, below the frequencies dominant in cetacean vocalizations and echolocation clicks (Fay, 1988), thus it is the low frequency disturbances that would be expected to provide the most significant acoustic input to most fish. The objectives of this study were to measure the source levels of some low-frequency sounds produced by bottlenose dolphins, *Tursiops truncatus*, and to estimate the range at which yellowfin tuna may detect these sounds.

Behavioral audiograms currently exist for yellowfin tuna, *Thunnus albacares,* and kawakawa, *Euthynnus affinis* (Iversen, 1967; Iversen, 1969). The yellowfin possesses a swimbladder and is considered a hearing generalist, that is, a fish with no known hearing specialization; the kawakawa is also a hearing generalist, but does not possess a swimbladder. Figure 1 illustrates the audiograms for yellowfin tuna and kawakawa. The symbols indicate the thresholds at each frequency measured for each of the two individual yellowfin tested by Iversen. The solid line is the mean yellowfin threshold at each frequency and is considered to be the hearing threshold for yellowfin. The best sensitivity occurs between 200–800 Hz, where the mean thresholds range from 89–100 dB *re*: 1 µPa. The audiogram for kawakawa has the same general shape as that of yellowfin, but the thresholds for kawakawa are approximately 10–20 dB higher.

Although some species of teleost fish have been shown to be sensitive to ultrasonic sounds, including clicks similar to those produced by dolphins or whales (Mann *et al*., 1998), there is currently no evidence to suggest high frequency sensitivity in the tuna. For this study, therefore, the source levels of breaches and tail slaps were of primary concern. A sound referred to as a “jaw pop” was also considered (Marten *et al*., 1988; Smolker and Richards, 1988). The production of this sound began with the animal shaking his head and emitting a series of high-frequency pulses, followed by an intense “pop” sound. At the sound emission, motion of the animal’s lower jaw was observed, hence the term “jaw pop.” The maximum audible range of these sounds was of primary interest, thus the lateral line system was not considered, though it may play a significant role in detecting these sounds close to the source.

Experimental measurements were performed to quantify the source levels typically encountered with these different sounds. The measured levels were then compared to published hearing thresholds for yellowfin tuna in order to estimate the maximum range at which *T. albacares* could detect these *Tursiops* sounds.

METHODS

Experimental animals

Table I lists the individual dolphins used in this study. Breachings were performed by both APR and MAK. Jaw pops and tail slaps were recorded from IAY and APR, respectively.

Jaw pop recordings

Jaw pops were recorded on two separate dates: 1 November 1983 and 1 June 1988. On each date, the animal was free swimming in a floating net enclosure, but remained in the same general location during the recordings.

Figure 2(a) shows the instrumentation used to record the jaw pops. The receive hydrophone was located approximately 1 m (1983) or 25 m (1988) from the animal. The hydrophone signal was conditioned and amplified using a B&K 2635 charge amp. The output from the charge amp was filtered and recorded on magnetic tape using a RACAL Store 7DS multitrack analog tape recorder. A separate voice track was also recorded to allow future identification of the signals. The tape speed was 60 ips for the 1983 data and either 15 or 60 ips for the 1988 data. The recording system frequency bandwidth was 0.1–75 kHz at 15 ips tape speed and 0.3–300 kHz at 60 ips. The recorded tapes were stored in a controlled environment, where they remained for several years.

The recorded signals were later digitized from tape using the instrumentation shown in Fig. 2(b). Large sections of tape, including the voice track, were first digitized at a relatively low sampling rate and converted to WAV files. The WAV files were then examined to locate the precise times of interest and the approximate signal strengths. This allowed the recordings to be played numerous times without adverse effects on the tape. The tapes were then played through the identified sections and the signals low-pass (anti-alias) filtered and digitized at 705.6 kHz and 88.2 kHz for the tapes recorded at 60 and 15 ips, respectively. The analog-to-digital (A/D) conversion was accomplished using an Iotech WaveBook/512 data acquisition system (12 bit A/D) and custom designed software.

Individual jaw pops were identified within the digitized data series and extracted in the form of 4–24 ms time windows. The peak-to-peak (p-p) source level, $SL_{p\text{-}p}$, and root-mean-square (rms) source level, SL_{rms}, were calculated for each jaw pop. The rms source level was calculated using:

$$SL_{rms} = 10\log_{10}\left(\frac{1}{T}\int_0^T p^2(t)\,dt\right), \tag{1}$$

where $p(t)$ is the recorded pressure and T is the signal duration (time window length). The narrowband pressure density spectrum, octave, and 1/3-octave band levels were also computed using a Fast Fourier Transform (FFT) algorithm.

Measured source levels are normally expressed as the sound pressure level (SPL) at a reference distance of 1 m. Equation (2) was therefore used to convert the SPL measured at a distance r from the source, SL_r, to the source level at 1 m, SL_1:

$$SL_1 = SL_r + TL, \tag{2}$$

where TL is the transmission loss. For the frequencies of interest, assuming spherical spreading, the transmission loss TL may be written as

$$TL = 20 \log(r) + a\, r, \tag{3}$$

where r is the distance from source to target (m) and a is the absorption coefficient (dB/m) (Kinsler *et al*., 1982). At 1 kHz the absorption coefficient $a \approx 0.00006$ dB/m, so the second term in Eq. (3) may be neglected at the frequencies considered here; at low frequencies and relatively short ranges the primary loss is due to the geometric (in this case spherical) spreading of the sound beam. The transmission loss is thus approximately equal to

$$TL \approx 20 \log(r). \tag{4}$$

Breach and tail slap recordings

The breach and tail slap recordings were carried out in a 9x18 m floating net enclosure in San Diego Bay on 7–8 August 1998. Figure 3 shows the experimental equipment. A B&K 8103 hydrophone was mounted to a pvc frame and submerged to a depth of 1.2 m. The hydrophone was located at the midpoint of one of the long sides of the pen and extended 0.75 m towards the pen interior. The output from the hydrophone was bandpass filtered (2 Hz to 30 kHz) and amplified using a B&K 2635 charge amp. The charge amp output passed through a long cable run (approximately 50 m) to the A/D input of a National Instruments PCI-MIO-16E-1 multifunction board residing within a personal computer. The data were sampled at 100 kHz with a resolution of 12 bits. The data acquisition was controlled using custom software. Hydrophone calibration was performed (using a B&K 4223 pistonphone) with the charge amp and long output cable in place.

A video camera was used to document each trial. The video was recorded with a stereo audio track consisting of both the airborne sound measured with a microphone and the underwater sound measured by a separate hydrophone located near the B&K 8103. During each trial, a PVC pipe was held underwater and struck to produce a single audible “clap.” This sound was recorded by both the video camera hydrophone and the B&K 8103 and used to synchronize the 8103 recording with the video.

The video and hydrophone recordings were examined offline to determine the timing of each breach or tail slap. The signals within these time windows were then digitally high-pass filtered (20 Hz cutoff frequency) and analyzed using a moving-window FFT algorithm to determine the envelope pressure density spectrum for each time series. This resulted in a composite spectrum containing the maximum spectral amplitude at each frequency. The octave and 1/3-octave band levels were also calculated from the envelope pressure density spectrum. The p-p source levels were calculated for the breaches and tail slaps; however, rms levels were not computed because the signal duration could not be accurately determined in each case.

RESULTS

Source levels

1. Jaw pops

Figure 4 shows the recorded time trace and spectrogram from a typical jaw pop recording. The jaw pops were typically produced when the animal became agitated; for example, in one instance they appeared directed at a wild California sea lion, *Zalophus californianus*, which had approached the netting of the animal’s pen. The actual pop was usually preceded by a precursor consisting of a number of intense pulses or clicks having p-p source levels up to 180–190 dB *re*: 1 µPa-m (1 µPa at a distance of 1 m). The precursor clicks have a rather high frequency content with the bulk of the power between 50–150 kHz. The actual jaw pop has a very broad spectrum with both low frequency (0–10 kHz) and high frequency (50–250 kHz) components.

Figures 5(a) and 5(b) show the time trace and pressure density spectrum, respectively, for a jaw pop. The time trace shows the signal amplitude at the receive hydrophone; the pressure density spectrum units have been scaled to a reference distance of 1 m using Eq. (2). The pop has a relatively short duration, on the order of 5 ms. The p-p and rms source levels are 189 and 167 dB *re*: 1 µPa-m, respectively, with the main signal power between 0.4 and 3 kHz. The low frequency roll-off at 300 Hz was caused by the tape machine frequency bandwidth at 60 ips.

Since much of the signal power exists at frequencies above the tuna's audible range, the rms level is not an appropriate measure of the actual stimulus to the tuna. The narrowband pressure density spectrum also does not seem appropriate because the use of a 1 Hz frequency bandwidth, while convenient, does not have any special significance to the auditory system of fish or any other vertebrates. To estimate the effective stimulus to the tuna, we therefore rely upon the concept of the critical bandwidth, which is "the frequency range within which the intensity of the stimulus summates over frequency in its effect on the auditory system" (Fay, 1988). The critical bandwidth concept approximates the ear as a bank of parallel bandpass filters, each with some finite bandwidth (the critical bandwidth). Critical bandwidths between 8% and 40% have been measured in goldfish and cod at center frequencies between 160 and 500 Hz (Hawkins and Chapman, 1975; Tavolga, 1974). These bandwidths are roughly in line with those of a 1/3-octave filter, which has a 23% bandwidth at all frequencies. For this reason, we define the effective source level SL_e as the maximum 1/3-octave level within the 200–800 Hz frequency range, which is the frequency range over which the yellowfin is most sensitive.

Figure 6 shows the octave and 1/3-octave band levels for the jaw pop from Fig. 5(a). The yellowfin audiogram from Fig. 1 is also included for comparison. The effective source level (SL_e) for this trial is approximately 145 dB *re*: 1 µPa-m. The mean SL_e and maximum SL_e from a total of 26 jaw pops were 149 and 163 dB *re*: 1 µPa-m, respectively.

2. Breaches

Figure 7 shows the pressure at the receive hydrophone during one of the breaching trials. As the animal, MAK, approached the water surface, it continuously echolocated, presumably to judge the distance to the surface. These echolocation clicks are clearly seen in Fig. 7, beginning near the 1.5 s mark and continuing until the animal became airborne near 4.5 s. The interclick interval decreased dramatically as the surface was approached. The animal remained airborne for approximately 1.5 s, during which the PVC pipe was struck to provide the timing reference as described previously. This produced the sharp transient visible near the 5.1 s mark. Finally, the animal re-entered the water near the 6.1 s mark, producing an initial transient (a “smack” sound) followed by lower frequency disturbances.

Figure 8 illustrates another breach recording. The upper trace shows the recorded time signal; the lower trace shows the spectrogram. The sharp click near 5.8 s is the timing reference. The re-entry sound occurs at approximately 6.8 s. A sharp transient is visible, again followed by lower frequency components. The landing sound has mostly low-frequency components, although the spectrum of the initial smack appears rather broad. It is clearly distinguishable from the timing reference, whose main energy lies above 1000 Hz.

Figure 9(a) shows a 1.2 s time window containing the re-entry sounds from the complete time record of Fig. 8. Figure 9(b) shows the pressure density spectrum, octave band, and 1/3-octave band levels. Note that the units for the ordinate are in dB *re*: 1 $\mu Pa^2/Hz$ for the pressure density spectrum and dB *re*: 1 μPa for the octave and 1/3-octave levels. The spectra are very broad and show significant components at frequencies up to approximately 1000 Hz. For this recording, SL_e is 160 dB *re*: 1 μPa-m.

A total of 11 breach recordings were examined. The p-p levels for all breach recordings varied from 168–191 dB *re*: 1 µPa-m. Effective source levels for all breaches varied from 126–160 dB *re*: 1 µPa-m. The mean value for SL_e was 149 dB *re*: 1 µPa-m.

3. Tail slaps

A total of six tail slap recordings were analyzed. Figures 10 and 11 show the time traces and frequency spectra for two representative examples. Note that the units for the ordinate are in dB *re*: 1 μPa^2/Hz for the pressure density spectrum and dB *re*: 1 µPa for the octave and 1/3-octave levels. The main spectral power from the tail slaps was often within the 100–600 Hz range. Effective source levels varied from 124–138 dB *re*: 1 µPa-m. The mean effective source level was 134 dB *re*: 1 µPa-m. The mean p-p tail slap level was 166 dB *re*: 1 µPa-m.

The source level measurements for the three different signal types are summarized in Table II.

Temporal summation

The tuna hearing thresholds presented in Fig. 1 are based on continuous wave (cw), pure tone stimuli. For finite duration sounds, thresholds decrease as the sound duration increases and eventually approach the cw value (Fay and Coombs, 1983; Hawkins, 1981). Temporal summation or integration such as this is a feature common to the auditory systems of all vertebrates (Fay, 1988). The sounds considered here are of relatively short duration, approximately 5–50 ms, therefore it seems reasonable to adjust (increase) the behavioral thresholds from Fig. 1 to include the effects of temporal summation.

No data exist for the effects of signal duration on the hearing thresholds in tuna. However, Fay and Coombs (1983) measured hearing thresholds in the goldfish as a function of stimulus duration for 200, 400, and 800 Hz pure tones and broadband noise. These data are plotted in Fig. 12 as the hearing threshold *re*: the cw threshold as a function of the stimulus duration. For the goldfish, the thresholds decrease as the signal durations increase up to approximately 800 ms, where the thresholds approach the cw value. A least-squares fit to all of the data was performed using the equation:

$$T = m \log(\quad) + b, \tag{5}$$

where T is the increase in dB over the cw threshold, is the stimulus duration in ms, and m and b are constants. The least-squares fit yielded $m = -8.3$ and $b = 23.5$. These data and Eq. (5) were used to estimate the expected increase to the tuna threshold for the jaw pop, breach, and tail slap sounds. The approximate duration and threshold increase for each signal type are displayed in Table III.

Range estimates

To estimate the maximum range at which the tuna could hear each of the different sounds, we assume that the effective source level minus the transmission loss equals the tuna average hearing threshold (within the 200–800 Hz band) plus the threshold correction for the finite stimulus duration:

$$SL_e - TL = T_{cw} + \quad T, \tag{6}$$

where T_{cw} is the cw threshold within the 200–800 Hz range. The transmission loss TL is given in Eq. (4), which assumes spherical spreading with zero absorption. Spherical spreading loss is a reasonable approximation given the water depth in the EPO (up to 5 km) (Rees, 1998) and the relatively short maximum audible ranges anticipated (less than 2 km). At the low frequencies considered here, absorption would not be a significant factor at ranges less than 2 km. Substituting Eq. (4) into Eq. (6) and solving for r yields:

$$r = 10^{(SL_e - T_{cw} - \Delta T)/20}. \tag{7}$$

Equation (7) was solved using the maximum SL_e and the minimum yellowfin hearing threshold (89 dB re: 1 µPa). This yields the maximum audible range for each signal type. Table IV lists the results. The jaw pops and breaches have similar values for the maximum audible range of approximately 850–900 m. The maximum estimated audible range for the tail slaps is 90 m.

DISCUSSION

We obtained direct measurements of source levels for some low-frequency sounds generated by *Tursiops* maintained in San Diego Bay, California and estimated the maximum distance that these sounds may be detected by yellowfin tuna, *T. albacares*. The dolphins generated three sounds: an internally generated sound referred to as a jaw pop, and two sounds produced by dolphin’s breaching and tail slap behaviors. The effective stimulus to the tuna was defined as the maximum sound pressure level generated within any 1/3-octave band between 200–800 Hz, the frequency range where *T. albacares* is most sensitive (Iversen, 1967). Published hearing thresholds for *T. albacares* were corrected upwards to account for the relatively short duration of the *Tursiops* sounds. Spherical spreading was assumed to predict transmission loss with range, and estimate the maximum detection distance for each sound. Breaches and jaw pops produced the highest source levels between 200–800 Hz (160 and 163 dB *re*: 1 µPa-m, respectively), and we estimate these *Tursiops* sounds could be detected at 850–900 m by *T. albacares*. The tail slaps were less intense (138 dB *re*: 1 µPa-m) and have a maximum detection range of approximately 90 m.

These estimates are in general agreement with Würsig and Würsig (1980), who stated that they could record similar sound from wild dolphins during optimal acoustic conditions (no wind, no waves) at a distance of 500 m but not at 1 km. Ambient noise will affect the ability of the tuna to discern these sounds from the background noise; however, because of the scarce data on hearing thresholds in tuna and complete lack of information regarding hearing of broad-band signals and the required signal to noise ratio, it is difficult to predict the effects of ambient noise, except to note that higher ambient noise levels will decrease the maximum audible range of these sounds.

Estimates of detection distance are also influenced by the directionality and transmission loss of the sound, as well as by the initial source level. Sounds produced by *Stenella longirostris* (Evans *et al*., 1964) and *Tursiops truncatus*, have been shown to be projected forward approximately 10–15° in both the horizontal and vertical planes (Au, 1986). The jaw pops reported here were recorded forward within 15° of the midline of the animal's head, however, the narrow 10–15° beam width has only been determined for frequencies above 30 kHz. Whether the jaw pops have such directionality is not known. An analysis of sound speed data from the EPO by Rees (1998) predicted "good to very good" horizontal propagation of 200–800 Hz frequency sound within the surface layer above the shallow thermocline. Signal directionality and reduced transmission loss would increase the detection distance estimate at any source level.

In addition to the jaw pop we measured, dolphins actively produce intense broadband clicks, pure tone whistles with harmonic structure, and numerous burst-pulse signals (Watkins and Wartzok, 1985; Norris *et al*., 1994), and are able to vary both the frequency and intensity of these sounds (Au, 1993). *Tursiops* trained to perform the sound-producing behavior on cue produced the sounds we measured. The breaching sounds resulted from leaps of approximately 1.5 to 2.5 meters, heights significantly less than the 3-4 meter leaps observed for *Delphinus delphis* and *Stenella spp.* in the wild. Tail slap sounds were recorded during very short trials because the dolphins quickly lost interest in performing the behavior. Many other aerial behaviors have been reported in *Stenella longirostris* and are thought to function in acoustic signaling (Norris *et al*., 1994).

We report on a small sample of dolphin-generated sounds obtained from three animals. We obtained the highest source level in the 1/3-octave band from

200–800 Hz with the *Tursiops* jaw pop sound (163 dB *re*: 1 µPa-m). Source levels obtained from cetaceans during repeated trials can exhibit fluctuations of 20-25 dB (e.g., see Table II). Source level measurements were further complicated by the difficulty of accurately measuring the distance between the animal and the receive hydrophone in each trial. These sources of variability, together with the scatter present in the yellowfin threshold data (as much as 11 dB at any one frequency), make estimating the detection range somewhat difficult – a cummulative error of 6 dB results in a doubling (or halving) of the estimated range. For this reason, we indicate the estimated maximum detection range of these sounds as 850–900 m, but also allow the possibility that it is greater.

The hearing thresholds for yellowfin were based on the mean values from the two individuals tested by Iversen (1967). The lowest threshold observed by Iversen for either fish was 83 dB *re*: 1 µPa at 500 Hz. If this value (rather than the lowest *mean* threshold of 89 dB *re*: 1 µPa) is used to estimate the maximum audible range for the jaw pops and breaches, the result is 1700–1800 m. It is also possible that Iversen's thresholds were masked by ambient noise at low frequencies, again allowing the possibility of larger maximum audible ranges for these sounds; however, ambient noise would likely be a limiting factor. Finally, Iversen's thresholds are for 50 and 60 cm fish, which are considerably smaller those typically associated with dolphin in the EPO. The effect of yellowfin size on hearing threshold is currently unknown. Together, these considerations leave open the possibility of maximum detection ranges greater than our estimate of 850–900 m.

The capacity to detect sounds in the 200–800 Hz range provides *T. albacares* the opportunity to detect some prey. Moulton (1960) contains spectrograms at these frequencies for anchovy schools, *Anchoviella choerostoma*, and Iversen *et al*. (1963) suggests squid may also produce sounds in these frequencies. *Stenella spp*. and *T. albacares* all feed on epipelagic fish, squid, and crustaceans in the EPO (Perrin *et al*., 1973). The combination of species-specific sounds produced by many individuals in a dolphin herd, and favorable oceanographic conditions for horizontal sound propagation, may provide the mechanism for the tuna/dolphin association in the EPO. In the absence of nearby prey, tuna may home on dolphin-produced sounds as part of their foraging strategy.

There is a wide range of reported peak frequencies and p-p source levels for cetacean generated sounds. Future measurements of source levels within the frequency band audible to *T. albacares*, for various sounds produced by *Stenella spp.* and *Delphinus delphis* in the EPO, may provide greater detection distance estimates than we report here. It is possible that under some conditions, especially very low noise conditions, detection distances could be greater than those reported here.

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Table I. Experimental animals used in this study.

name	species	age	weight (kg)	sex	task
IAY	*Tursiops truncatus gilli*	19[a]	255[a]	M	jaw pops
APR	*Tursiops truncatus*	14	169	F	breach/tail slaps
MAK	*Tursiops truncatus*	28	207	M	breach

[a] c. December 1983

Table II. Measured source levels for each signal type.

	SL_e		$SL_{p\text{-}p}$		SL_{rms}		
	mean	range	mean	range	mean	range	
jaw pop	149	125–163	194	176–201	173	153–181	dB *re*: 1 µPa-m
breach	149	126–160	179	168–191	–	–	dB *re*: 1 µPa-m
tail slap	134	124–138	166	162–169	–	–	dB *re*: 1 µPa-m

Table III. Effects of temporal summation for the three signal types.

	duration (ms)	ΔT, threshold (*re*: cw threshold)
jaw pop	10	15
breach	25	12
tail slap	50	9

Table IV. Estimated audible ranges for yellowfin tuna hearing thresholds for each type of *Tursiops* signal.

	maximum range (m)
jaw pop	850
breach	900
tail slap	90

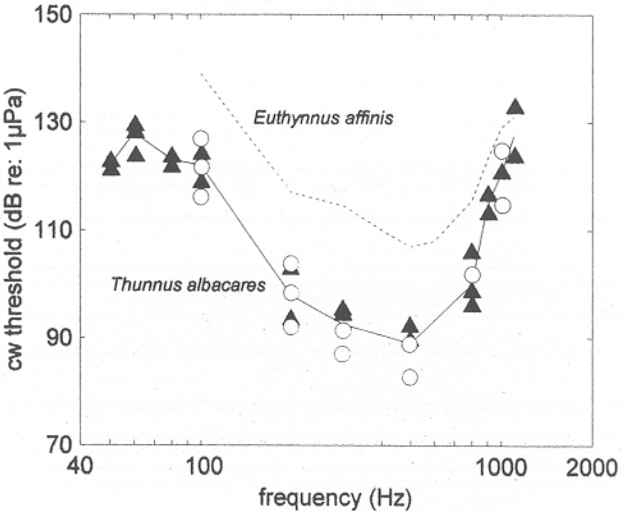

FIG. 1. Behavioral audiograms for two species of tuna: *Thunnus albacares* (yellowfin tuna) (Iversen, 1967) and *Euthynnus affinis* (kawakawa) (Iversen, 1969). The symbols are the thresholds measured from two individual yellowfin; the solid line indicates the mean yellowfin threshold. The dashed line is the mean kawakawa threshold from two individuals.

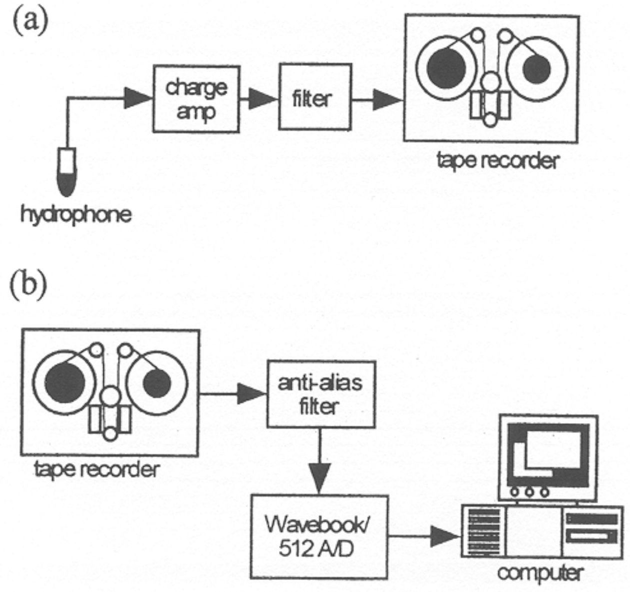

FIG. 2. Experimental setup for the (a) jaw pop recording to tape and (b) digitization and transfer of data to computer hard disk.

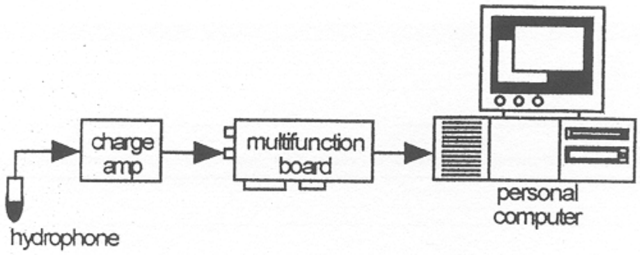

FIG. 3. Experimental setup for the breach and tail slap recordings.

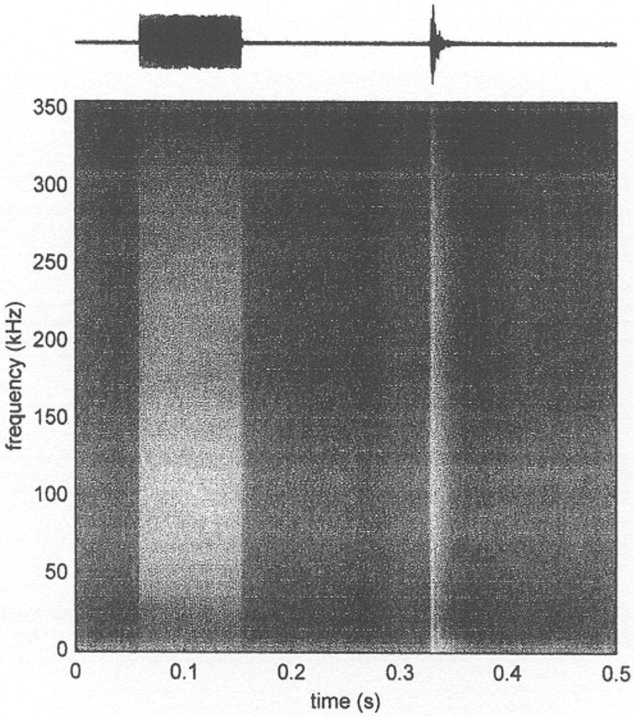

FIG. 4. Time trace (upper) and spectrogram (lower) for a typical jaw pop and its precursor.

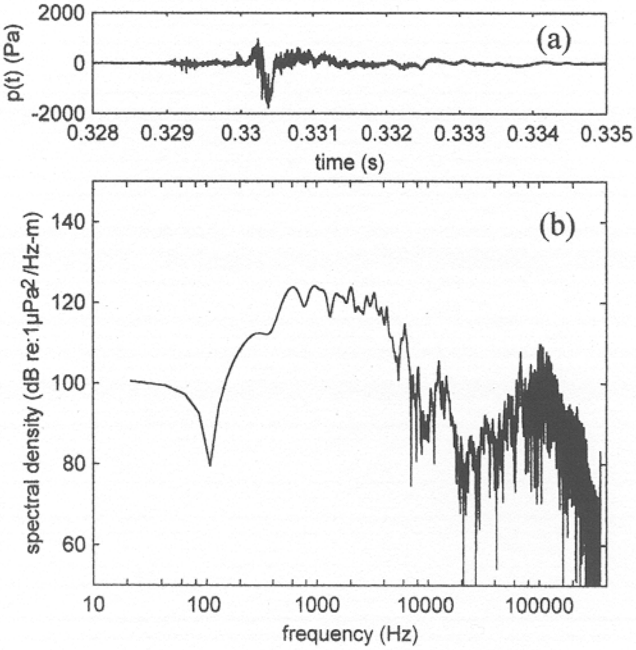

FIG. 5. (a) Time trace and (b) pressure density spectrum for a typical jaw pop. The analysis frequency bandwidth was 21.5 Hz.

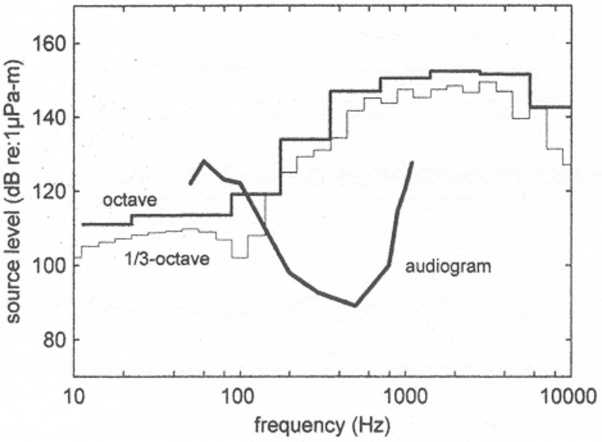

FIG. 6. Octave and 1/3-octave band levels of the jaw pop from Fig. 5(a). The yellowfin audiogram is also included for comparison.

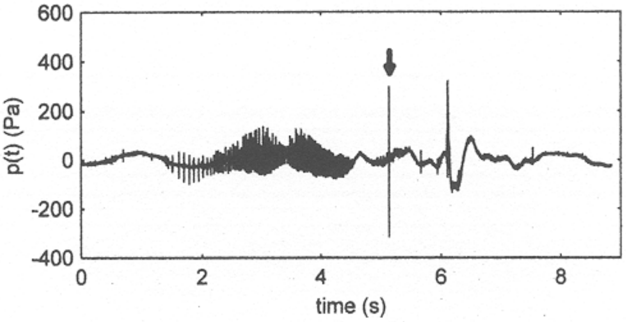

FIG. 7. Time trace for a typical breach recording. The arrow indicates the timing reference.

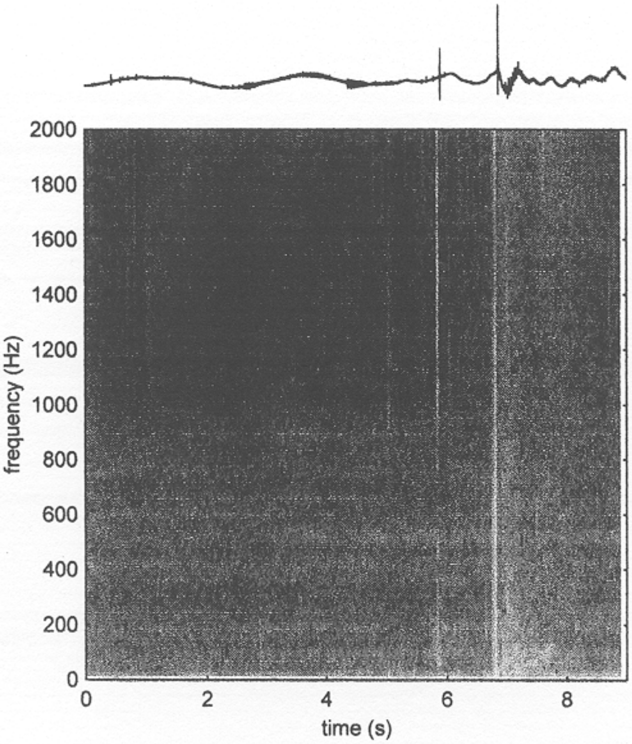

FIG. 8. Time trace (upper) and spectrogram (lower) for a typical breach recording. The arrow indicates the timing reference.

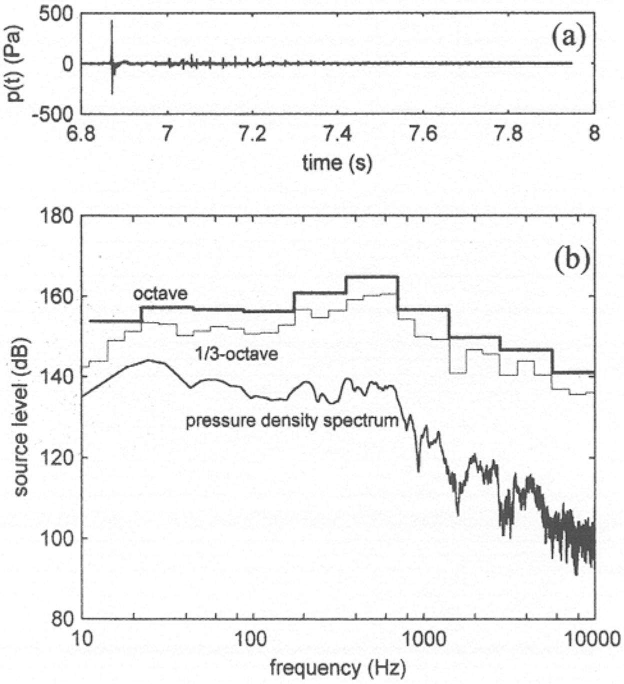

FIG. 9. (a) Time trace and (b) pressure density spectrum, octave, and 1/3-octave band levels for the re-entry sounds from Fig. 8. The dB reference is 1 μPa^2/Hz for the pressure density spectrum and 1 μPa for the octave and 1/3-octave levels. The pressure density spectrum bandwidth is 6.1 Hz.

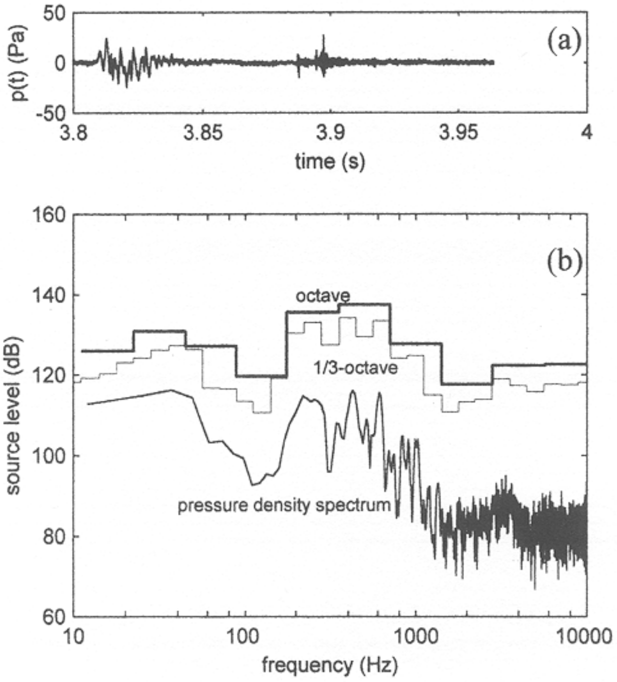

FIG. 10. (a) Time trace and (b) pressure density spectrum, octave, and 1/3-octave band levels for a tail slap recording. The dB reference is 1 μPa^2/Hz for the pressure density spectrum and 1 μPa for the octave and 1/3-octave levels. The pressure density spectrum bandwidth is 12.2 Hz.

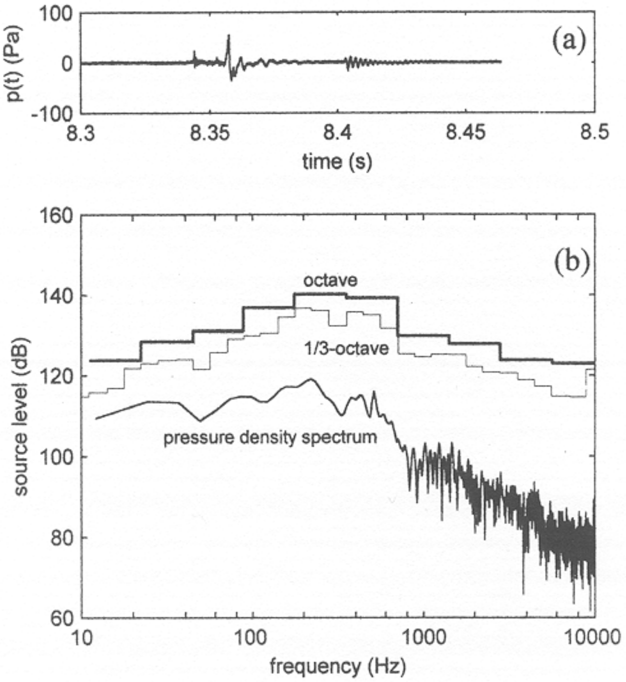

FIG. 11. (a) Time trace and (b) pressure density spectrum, octave, and 1/3-octave band levels for a tail slap recording. The dB reference is 1 μPa^2/Hz for the pressure density spectrum and 1 μPa for the octave and 1/3-octave levels. The pressure density spectrum bandwidth is 12.2 Hz.

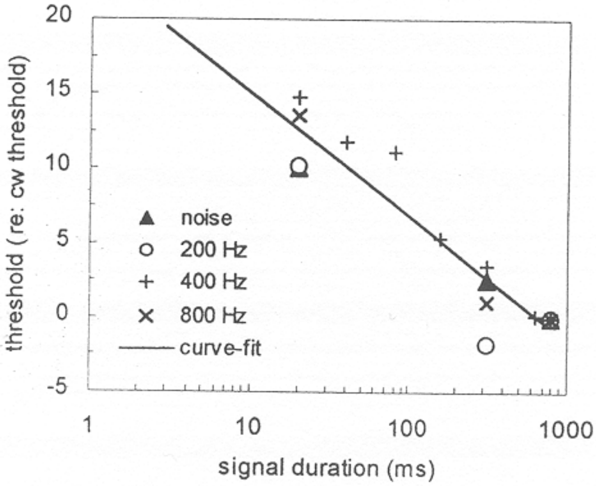

FIG. 12. Hearing thresholds in goldfish as functions of the signal duration (Fay and Coombs, 1983).