

Measurement of an individual silver perch *Bairdiella chrysoura* sound pressure level in a field recording

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Simultaneous audio and video were recorded of a silver perch *Bairdiella chrysoura* producing its characteristic drumming sound in the field. The background noise contribution to the total sound pressure level is estimated using sounds that occurred between the pulses of the silver perch sound. This background contribution is subtracted from the total sound to give an estimate of the sound pressure level of the individual fish. A silver perch source level in the range 128–135 dB (*re*: 1 μ Pa) is obtained using an estimate of the distance between the fish and the hydrophone. The maximum distance at which an individual silver perch could be detected depends on the background sound level as well as the propagation losses. Under the conditions recorded in this study, the maximum detection distance would be 1–7 m from the hydrophone. © 2004 Acoustical Society of America. [DOI: 10.1121/1.1802651]

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I. INTRODUCTION

A. Fish sound production

Many fishes produce species-specific sounds (Fine *et al.* 1977; Fish and Mowbray 1970; Mann *et al.* 1997; Myrberg 1981; Myrberg *et al.* 1965) associated with aggression, aggregation, fright, and reproductive behaviors (Winn 1964). The males of Family Sciaenidae (drums and croakers) produce species-specific courtship “drumming” sounds at spawning sites (Connaughton and Taylor 1995, 1996; Fish and Mowbray, 1970; Luczkovich *et al.*, 1999b; Mok and Gilmore 1983). These spawning-related sounds have been used by scientists and fisheries managers to delineate areas where spawning occurs (Luczkovich *et al.* 2000, 1999a, b). Luczkovich *et al.* (1999a, b) demonstrated that the sound pressure levels of silver perch *Bairdiella chrysoura* and weakfish *Cynoscion regalis* drumming each correlate with densities of fertilized conspecific eggs in the water column. Although information about egg production is important, scientists and fisheries managers would like a technique for estimating fish populations, especially spawning populations. Individual source levels are required in order to use passive acoustics for fish population estimates.

B. Measurement of fish sound pressure levels

Fish sounds have been measured both in nature (Luczkovich *et al.* 1999b) and in captivity (Guest and Lasswell 1978; Sprague *et al.* 2000), but the source level of an individual in the natural environment has never been precisely determined. In captivity, reflections from tank walls compli-

cate the relationship between measured individual source levels and those produced in nature (Akamatsu *et al.* 2002). Connaughton *et al.* (1997, 2000) avoided the complications of tank reflections by measuring disturbance sounds produced by captive weakfish in air and found that the sound levels increased significantly with fish size, temperature, and sonic muscle condition. Most sciaenid fishes live in turbid waters and spawn at night. In this low-visibility environment, it is often difficult to determine important parameters such as the distance to and identity of a sound-producing fish. Luczkovich *et al.* (1999b) report that the maximum sound pressure level they recorded for an “individual” silver perch sound was 136 dB and assumed that the individual producing the sound was very near their hydrophone, although there was no confirmation of this assumption. The maximum sound pressure level measured during that study was 147 dB, but this was for a chorus of weakfish and silver perch together with background noise. Individual fish could not be distinguished in that recording (Luczkovich *et al.* 1999b).

In North Carolina (USA) waters, where sciaenids are acoustically dominant, fish sound production begins just before sunset and lasts into the night (Sprague *et al.* 2000). Sounds produced by large aggregations of drumming sciaenids blend together obscuring individual calls. Even when an individual fish sound is identifiable, it must be separated from the background noise in order to determine its sound pressure level.

C. Sound and video recording

On May 5, 2001 we obtained audio and video of a silver perch producing its drumming sounds at Wallace Channel in Ocracoke Inlet, North Carolina. In this paper we analyze the

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audio and video to estimate the background sound pressure level and estimate the sound pressure level of the individual fish.

II. THEORY

A. Combining sounds from incoherent sources

Sound pressures measured by a sound meter are given by

$$p_{\text{rms}}(t) = \left[\frac{1}{t_c} \int_{-\infty}^t p^2(t') e^{(t'-t)/t_c} dt \right]^{1/2}, \quad (1)$$

where $p_{\text{rms}}(t)$ is the rms pressure read on the meter at time t , $p(t')$ the instantaneous pressure at time t' , and t_c the time constant of the meter. Equation (1) can be approximated for a sound discretely sampled at frequency f_0 as

$$(p_n)_{\text{rms}} = \left[\frac{1}{f_0 t_c} \sum_{k=1}^n p_k^2 \exp\left(\frac{k-n}{f_0 t_c}\right) \right]^{1/2}, \quad (2)$$

where the $(p_n)_{\text{rms}}$ represents the rms pressure at the time of sample n and p_k the acoustic pressure at the time of sample k .

We assume that each fish in an aggregation produces sound independently from the others (i.e., there is no fixed phase relationship between each sound source). Hence, each sound source is approximately incoherent. The time average pressure-squared is the sum of the pressures-squared for each mutually incoherent source (Pierce 1989). With an individual fish can be heard over a background, the total average pressure-squared is

$$p_{\text{av}}^2 = (p_f^2)_{\text{av}} + (p_{\text{bg}}^2)_{\text{av}}, \quad (3)$$

where p_f is the acoustic pressure of the individual fish and p_{bg} the acoustic pressure of the background sound. The subscript ‘‘av’’ in Eq. (3) indicates a time average. The time average pressure-squared p_{av}^2 is approximated by the square of the rms pressure measured by a sound meter.

B. Sound pressure levels and source levels

The sound pressure level in decibels is a logarithmic measure of sound pressure, given by

$$L = 20 \log_{10} \frac{p_{\text{rms}}}{p_0}, \quad (4)$$

where p_0 is the reference pressure (1 μPa for underwater measurements and throughout this paper). Sound pressure levels in decibels must be converted to pressure units before using them in Eq. (3). Pierce (1989) introduced a background correction factor C_{bg} for computing sound pressure levels when incoherent background noise is present. Using the notation in Pierce (1989), the sound pressure level of the individual fish L_f can be represented as

$$L_f = L - C_{\text{bg}}(L - L_{\text{bg}}), \quad (5)$$

where L is the total sound pressure level, and L_{bg} the sound pressure level of the background sound. The function C_{bg} is the background correction factor, which is

$$C_{\text{bg}}(\Delta L) = -10 \log_{10}(1 - 10^{-\Delta L/10}), \quad (6)$$

where $\Delta L = L - L_{\text{bg}}$ is the difference between the total and background sound pressure levels. Equations (5) and (6) can be used to obtain the fish sound pressure level L_f if the total sound pressure level L and the background sound pressure level L_{bg} can be measured.

The source level is defined as the sound pressure level at a distance of one meter from the sound source under free-field conditions. Since sound spreads spherically at distances smaller than the water depth (Urlick 1983), we can use the spherical spreading model,

$$p_{\text{rms}}(r) = r_0 \frac{p_s}{r}, \quad (7)$$

to determine the source level. In Eq. (7), $p_{\text{rms}}(r)$ is the rms acoustic pressure at distance r , r_0 the reference distance (1 m), and p_s the rms acoustic pressure at distance r_0 from the source. Using Eqs. (4) and (7), the source level is

$$L_s = 20 \log_{10} \frac{p_s}{p_0} = 20 \log_{10} \left[\frac{r p_{\text{rms}}(r)}{r_0 p_0} \right]. \quad (8)$$

C. Maximum detection distance

The maximum detection distance r_{max} for a sound depends on the background sound level as well as the propagation losses as the sound travels between the source and receiver. A sound can be accurately detected above the incoherent background when its sound level is greater than or equal to the background sound level (Pierce 1989). The propagation losses in shallow water depend on many parameters including water depth, bottom type, variations in sound speed, and water currents with depth and horizontal position. Precise measurements of propagation losses are particular to the properties of a given location, but estimates of minimum propagation loss can be made using geometrical spreading laws. Sound spreads spherically at distances less than the water depth [see Eq. (7)] and cylindrically at distances much greater than the water depth (Urlick 1983). Solving Eqs. (4) and (7) for the distance at which the sound level is equal to that of the background under spherical spreading conditions

$$r_{\text{max,sph}} = r_0 10^{(L_s - L_{\text{bg}})/20}. \quad (9)$$

The cylindrical spreading model is

$$p_{\text{rms}}(r) = \sqrt{r_0} \frac{p_s}{\sqrt{r}}. \quad (10)$$

Solving Eqs. (4) and (10) for the distance at which the sound level is equal to that of the background under cylindrical spreading conditions

$$r_{\text{max,cyl}} = r_0 10^{(L_s - L_{\text{bg}})/10}. \quad (11)$$

The predicted value for r_{max} is $r_{\text{max,sph}}$ for distances less than the water depth and $r_{\text{max,cyl}}$ for distances much greater than the water depth. There is a transition region at distances close to the water depth at which the propagation losses are between those predicted by spherical spreading and those predicted by cylindrical spreading (Urlick 1983). At these distances r_{max} is between $r_{\text{max,sph}}$ and $r_{\text{max,cyl}}$.

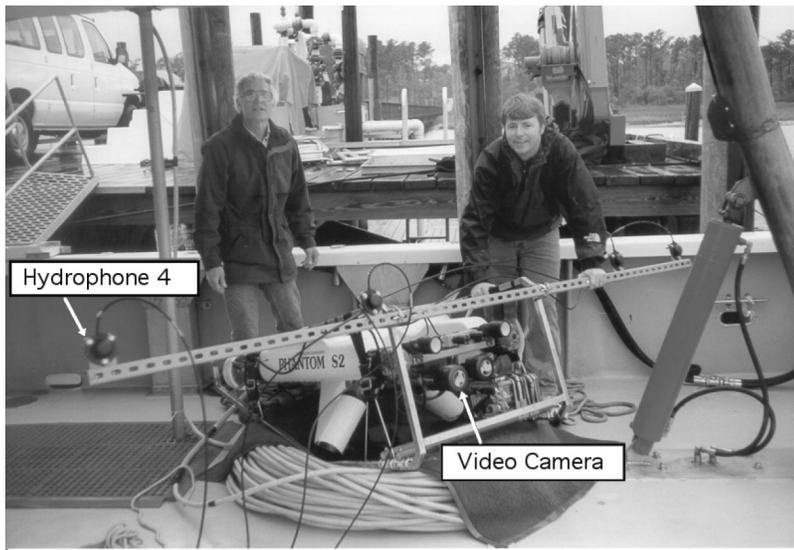


FIG. 1. Phantom S2 ROV with hydrophone boom. The audio signal was recorded by Hydrophone 4 on the starboard side of the vehicle as indicated in the figure, and the video was recorded by the video camera on the body of the ROV. Pictured are the ROV pilot (Glenn Taylor, left) and the one of the authors (Mark W. Sprague, right). Photo by Joseph J. Luczkovich.

III. METHOD

We recorded simultaneous sound and video using a hydrophone (ITC, Model 4066) mounted on a Phantom S2 remote operated vehicle (ROV) with on-board low-light video cameras. (See Fig. 1.) The hydrophone signal was recorded onto the left channel of an audio-cassette recorder (Sony model CFS-1055) while commentary recorded using a microphone on the research vessel was recorded onto the right channel. The video signal was recorded to a VHS recorder which also inserted a time display on the recording. Electrical problems on the research vessel prevented us from recording the hydrophone signal directly onto the audio track without 60-Hz interference or analyze all four hydrophone signals simultaneously, but we were able to match the sound recording from Hydrophone 4 with the video recording to within ~ 0.5 s by announcing the time recorded on the video track onto the commentary recording.

The ROV was deployed in Wallace Channel (latitude: $35^{\circ} 04' 21.814''$ N, longitude: $76^{\circ} 02' 59.325''$ W) in 10–11-m deep water at a location we had previously documented as silver perch spawning site (Luczkovich *et al.* 1999a). Due to large tidal currents in the inlet, the ROV could not maneuver effectively with its motors. We used a 20-kg downweight attached to the bridle to anchor the ROV to the sea-floor for use as an audio and video platform.

We calibrated the sound recording system by comparing it to a calibrated hydrophone system (Inner Ocean902). We placed the calibrated hydrophone less than 1 cm from the measurement hydrophone, and played a sequence of tones over the frequency range of interest (300–5000 Hz) recording the signals from both hydrophone systems. There was little variation between the two systems over the entire frequency range. We used the calibration value from the peak frequency range of the silver perch sound (700–1200 Hz) to calibrate the measurement system.

We digitized the sound recording at a sampling frequency of 24 kHz using an analog-to-digital board (National Instruments NB-2150F) connected to a Macintosh computer. A sonogram was computed from the digitized sound file using a 1024-point Hanning-windowed fast Fou-

rier transform (FFT) with each window overlapping the previous window by 512 sample points.

We computed sound pressure levels for the entire sound recording using Eq. (2) and used Eq. (5) to obtain the fish sound pressure level during the peak of each pulse in the silver perch sound. We estimated the background level using the sound pressure level between the pulses of the silver perch sound. Local maxima of background sound pressure level were used to construct an interpolated maximum background sound pressure level. Similarly, local minima of the background sound pressure level were used to construct an interpolated minimum background sound pressure level. We used the interpolated maximum and minimum background sound pressure levels to determine minimum and maximum values (respectively) for L_f in Eq. (5) for each silver perch pulse.

IV. RESULTS

We began recording audio at 20:25 local time and recorded continuously until 22:36 local time. Although we heard silver perch in the background during the two-hour recording, we only heard an individual silver perch (i.e., an individual fish sound distinguishable above the background noise from fish aggregations) during one segment. We observed a silver perch swim in front of the ROV toward Hydrophone 4 on the starboard side and, at the same time, recorded audio of the silver perch sound on Hydrophone 4. The fish entered the video at time 6 s (22:18:07 local time) and swam off the right of the screen at time 10 s (22:18:11 local time). The silver perch sound pressure level reached a maximum between times 15–18 s (22:18:16–22:18:19 local time) when the fish swam by Hydrophone 4. A sonogram (Fig. 2) shows that the silver perch pulses, seen as dark lines from 700–1200 Hz, are loudest between times 15.75 and 17.50 s. Figure 3 shows a plot of the total sound pressure level, maximum and minimum background noise estimates, and estimates of the maximum silver perch sound pressure level for each sound pulse. The maximum silver perch received sound pressure level in the entire recording of 128 dB, using the estimated maximum background sound pres-

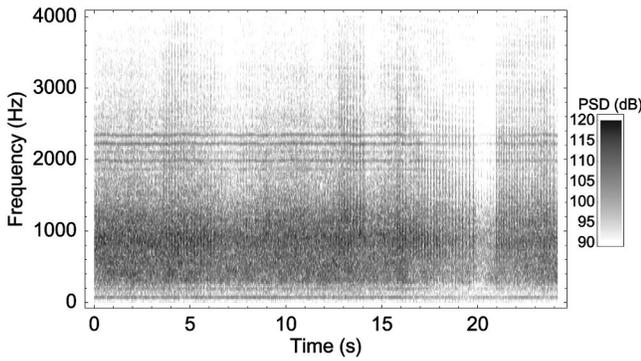


FIG. 2. Sonogram of silver perch recording from Hydrophone 4. Each power spectrum was computed from a 1024-sample Hanning window which overlapped the previous power spectrum by 512 sample points.

sure level and 129 dB using the estimated minimum background sound pressure level occurred at time 15.85 s in the recording. All of the other pulses from 15.75–17.50 s had silver perch received sound pressure levels from 127–129 dB.

V. DISCUSSION

In order to know the silver perch source level precisely, we must know its distance from the hydrophone. Our encounter with the silver perch was a fortuitous event. Although we were not able to determine the exact distance between the silver perch and the hydrophone, the video allows us to confirm its proximity. We can say with reasonable confidence that the fish was within 1–2 m of Hydrophone 4 when we recorded the sound. This allows us to establish a minimum source level of 128 dB for an individual silver perch in field conditions. If the silver perch were 2 m from the hydrophone the source level could be as high as 135 dB (assuming spherical spreading and minimum background noise). The sound pressure level that we have measured with our calibrated hydrophone system on the ROV at Wallace Channel in 2001 corresponds well with levels for individual

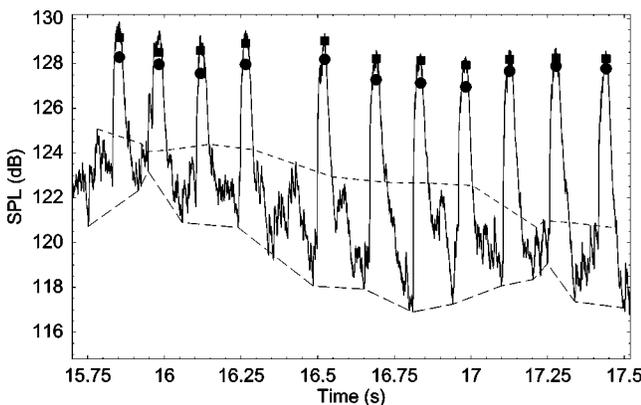


FIG. 3. Sound pressure levels computed from the silver perch recording from Hydrophone 4. The black curve is the total sound pressure level computed with a time constant of 0.01 s. The short-dash and long-dash curves are estimates of the maximum and minimum background sound pressure levels, respectively. The circles and squares represent the estimated peak silver perch sound pressure level for each pulse computed using the maximum and minimum background sound pressure levels (respectively) in Eq. (5).

silver perch that were an unknown distance from the hydrophone as reported by Luczkovich *et al.* (1999b). Those authors measured a maximum of 136 dB on 13 recordings made at similar inlet locations in 1997. However, the result obtained here was for a single fish. We have no estimate of variability for silver perch that are a known distance from the hydrophone. Nonetheless, this result is important because nobody has ever measured the source level of a sciaenid fish calling *in situ*.

We do not have conclusive proof that the silver perch observed on the video was the fish producing the sound. However, it is highly unlikely that another fish produced the sound, because we never recorded another individual silver perch on audio or video near the ROV at Wallace Channel, even though we recorded continuously for over two hours on May 5th. Additionally, we recorded with the ROV's video and audio at a nearby station on May 2nd–4th for nearly two hours in the evening, at Wallace Channel on May 4th for two hours in the evening, and for a total of 56 min on May 8th, with 12 short recordings made at hourly intervals through an entire tidal cycle (from 11:25 until 23:18 local time), without encountering an individual silver perch near the ROV. We conclude that the co-occurrence of the very loud silver perch sounds with the appearance of a silver perch swimming into the video cameras viewing area strongly implicates it as the sound producer in this recording. Further work using hydrophone arrays to localize the source of the sound producers and determine the spatial distribution of these fishes on the spawning grounds is needed.

An important application of these data is the maximum distance r_{\max} at which a fish can be detected above the background level. The background levels during our recording session varied between 118 and 125 dB. The maximum distance at which an individual silver perch could be detected above the background noise in this environment would depend on the background sound pressure level (see Table I). When the background sound is loud (125 dB), r_{\max} is less than the water depth (10 m), and spherical spreading dominates. When the background sound is quiet (110 dB), r_{\max} is much greater than the water depth and cylindrical spreading dominates. At midlevel background noise (118 dB), r_{\max} is likely between the spherical and cylindrical spreading distances.

The biological significance of these computations is that both what a fisheries biologist can detect and what another fish or predator can detect will be affected by background sound. For example, an individual silver perch calling with source level between 128 and 135 dB will be heard above the background by a biologist doing a passive acoustic survey with hydrophone similar to ours at between 1.4 and 3.2 m away (r_{\max}), assuming spherical spreading and a maximum background level of 125 dB. This distance will vary with background levels at the location and the sound spreading model (cylindrical or spherical) used, as shown in Table I. Thus, the estimates of r_{\max} provided by Luczkovich *et al.* (1999b), which assumed an individual weakfish (*Cynoscion regalis*) calling at 127 dB, cylindrical spreading and 110 dB as a background level, were relatively large (50 m). However, a more typical situation for the biologist doing a pas-

TABLE I. Maximum detection distance for an individual sound, r_{\max} .

Estimated source level	Spreading model and background level					
	Spherical			Cylindrical		
	110 dB	118 dB	125 dB	110 dB	118 dB	125 dB
128 dB (minimum)	7.9 m	3.2 m	1.4 m	63 m	10 m	2.0 m
135 dB (maximum)	18 m	7.1 m	3.2 m	316 m	50 m	10 m

sive acoustic survey will be a recording made with other fish calling in the background (118–125 dB), resulting in r_{\max} distances that are relatively small (1–7 m for spherical spreading model and 2–50 m for the cylindrical model). In shallow water (~ 10 m), the choice of model will depend on the background sound at the site, with spherical model being favored at high background levels and cylindrical model at low background levels. Thus, at our measured background levels (118–125 dB caused by other fish chorusing) an individual fish calling could only be detected above the background chorus at 1–7 m range. On a quiet morning, when background levels are 110 dB (Luczkovich *et al.* 1999b), an individual calling at 135 dB could be heard at an r_{\max} of 316 m. For the loudest background level recorded in this area, 147 dB (Luczkovich *et al.* 1999b), an individual silver perch 1 m from the hydrophone would be undetectable. These calculations provide an upper and lower bound for r_{\max} under conditions measured in actual field situations that will be encountered by biologists, and thus provide a basis for developing calibrated passive acoustic survey techniques.

We can now set a threshold for sound detection of an individual silver perch that is close to an autonomous recording system, so the system can be automatically triggered when it exceeds the level described here. That is, if a sound is detected that is 128 dB or louder and has similar spectral properties to silver perch sounds (Sprague *et al.* 2000), then the system can be automatically triggered to photograph or record the sound producer. Such a remote sensing system is achievable with current technology and can be deployed in multiple locations, saving money and time associated with surveying fish populations. This approach, with similar source level measurements, could be used to remotely sense cod *Gadus morhua*, sturgeon *Acipenser* sp., red drum *Sciaenops ocellatus*, or any soniferous species.

Additionally, the female silver perch would only be likely to hear a calling male at this range (r_{\max}). Obviously, males that called louder than the background would be more likely to be heard by biologists, female silver perch, and bottlenose dolphin (*Turisops truncatus*), one of their major predators that also use sound to detect their prey (Luczkovich *et al.* 2000). So there are trade-offs for the fish to consider when calling, and the fish may modulate their sounds to be not too much louder than the background. We have no data on this, but note that some choruses seem to increase and decrease in sound pressure level (Luczkovich *et al.* 2000).

An aggregation of silver perch can be heard at a much larger distance than an individual. In this study, the sound of other silver perch was likely to be an aggregation at some distance away. The maximum distance that an aggregation

can be detected depends on how many fish are in the aggregation and their spatial distribution as well as the variation in water depth and properties. It is beyond the scope of this study to model the properties of silver aggregations until we have better information on these parameters, but our calculations provides a first step toward this ultimate goal.

VI. CONCLUSION

We measured simultaneous audio and video of a calling silver perch in the field and determined its maximum sound pressure level by estimating the background noise. Using an estimated distance between the fish and our hydrophone, we calculate the silver perch source level between 128 and 135 dB. This information is useful for modeling distributions of fishes and developing algorithms of automatic detection of sound-producing fishes by autonomous sound recorders.

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