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2pAB8. New observations and modeling of an unusual spatiotemporal pattern of fish chorusing off the southern California coast

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The purpose of this presentation is to present new results on an unusual spatiotemporal pattern of fish chorusing off the southern California coast. Characteristics of this fish chorus have been reported previously; it occurs at night in the late spring and summer months in shallow, sandy bottom regions just outside the surf zone. The background sound levels increase by up to 30 dB and cycle in level with a period of 30-35 sec all night long. In this paper, recent results from measurements made by a set of high spatial resolution sensor systems spanning a 50-km stretch of coastline out to 20 km offshore over a 2-month time period are presented. These data allow the spatial dependence and long-term temporal variability of the chorus to be examined at high spatial resolution. Refinements to a numerical model that predicts this chorusing behavior are required to account for some aspects of these new observations. [Work supported by the Office of Naval Research, Code 322-MMB].

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INTRODUCTION

Underwater biological choruses occur when a large number of animals, often of a single species, create sound simultaneously over a significant period of time (Tavolga, 1964; Cato, 1978). A variety of choruses have been identified in ocean acoustic recordings off the southern California coast, e.g., (?D'Spain *et al.*, 1997). Most of the original descriptions of these choruses appear in technical reports published by scientists at the Navy laboratory in San Diego, CA, now called the SPAWAR Systems Center Pacific (for example, refer to (Wenz *et al.*, 1965)). These choruses dominate the underwater sound field at certain times and locations, over certain frequency bands. The biological chorus described in this paper increases the background levels by 20-30 dB over the 300-600 Hz band during the nighttime in the spring and summer months in the nearshore region off the southern California coast.

Previous research on this chorus used data collected in 1995 from two connected hydrophone line arrays deployed in 20-m-deep water 3.5 km off the coast at Marine Corp Base Camp Pendleton (D'Spain *et al.*, 1997). These data indicate that the individual fish sounds comprising the chorus are a series of 7-13 transients. The sound is similar to that of someone knocking on wood. The time interval between "knocks" in a given sequence is nearly constant. However, histograms of these time intervals obtained from a few hundred knocking sequences separate into two distinct families - one with a mean time interval of about 0.5 sec and a second with a time interval of 0.75 sec. One interpretation is that these two types of knocking sequences are created by two distinct, but biologically-similar, species of fish that contribute to the chorus.

The objective of this paper is to present new results on this unusual biological chorus, obtained from a high spatial resolution ocean acoustic data set with extensive spatial coverage. These data were acquired in 1999 off the southern California coast. A brief description of the experiment is provided in the next section, followed by the section in which selected data processing results are presented. Discussion of these results and concluding remarks are provided in the final section.

EXPERIMENT AND DATA PROCESSING

In 1999, a large experiment was conducted off the southern California coast involving the deployment of several hydrophone line arrays on the ocean bottom. The data from these arrays were fiber-optic cabled to shore and recorded continuously over the 2-month period April/May, 1999. The locations of the 6 arrays nearest to shore are plotted in Fig. 1. These array locations span the coastline from San Clemente in the north to south of Oceanside, CA. Most of the area between these two cities comprises the Marine Corp Base Camp Pendleton. On the northwest border of Camp Pendleton lies the San Onofre Nuclear Generating Station (SONGS), where several studies have been conducted on the fish entrapped by the offshore intake structures of its seawater cooling system, e.g., (Allen *et al.*, 2003; Miller *et al.*, 2011).

RESULTS TO DATE

To illustrate the characteristics of the nighttime chorus, a 10-min spectrogram from the data recorded by a single element in Array 14 (the array in the approximate center of Fig. 1, nearly due south of SONGS), is presented in Fig. 2. A total of 19 vertical bands of higher-energy sound occur over the 10-min period, equal to an average rate of occurrence of once every 32 sec. The spectrogram reaches levels around 85 dB re 1 $\mu Pa^2/Hz$ in the 300-500 Hz band. The vertical bands extend from below 300 Hz up to the maximum frequency in Fig. 2 of 850 Hz. The chorus recorded at the other arrays decay to background levels at somewhat lower frequencies, due to the greater distance of these arrays from the sources of the sounds.

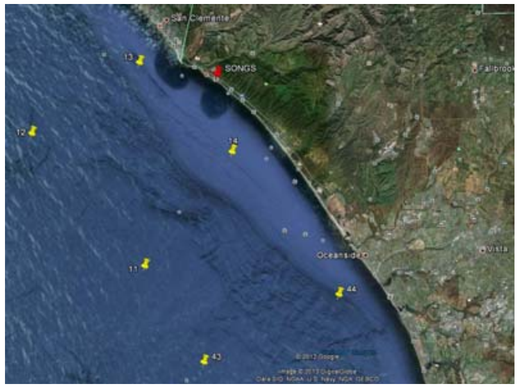

FIGURE 1: The locations of the 6 hydrophone line arrays (labeled 13, 14, 44, 12, 11, and 43) deployed off the southern California coast in March-May, 1999 are plotted with yellow "push-pin" symbols on this Google Earth map. The red "push-pin" marks the location of the San Onofre Nuclear Generating Station ("SONGS") on the coast just northwest of Marine Corps Base Camp Pendleton.

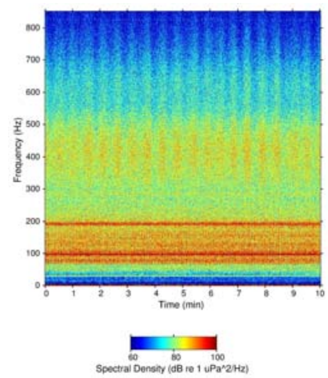

FIGURE 2: This single element spectrogram from Array 14 covers a 10-min time period (horizontal axis) near 11 pm local time on 9 May, 1999 (05:48 Z, 10 May). The frequency (vertical) axis spans the 0-850 Hz band. The spectral density has been properly calibrated for the array system response above 100 Hz.

The spatial dependence of the chorus received levels for a 10-min period over the region covered by Fig. 1 is illustrated in Fig. 3. To create the curves in this figure, the spectral density recorded by a single element in each of the 6 arrays was integrated over the 300-600 Hz band. The mean of the sound pressure levels recorded by Array 14 (red curve) is 4-5 dB higher than that of the next highest levels recorded by Array 13 (blue curve), which is the array farthest north and nearest to San Clemente. Array 14's location therefore may be closer to the sources of these chorus sounds than the other arrays. The levels recorded by Array 44 (green curve), the third nearest-to-shore array and closest to Oceanside, are about 12 dB down from those at Array 14, and just a few decibels greater than those recorded by the three offshore arrays. Part of the reason for these decreased levels at nearshore Array 44 is that this array was deployed in significantly deeper water, almost 180 m, compared to Arrays 13 and 14 deployed in water depths less than 60 m. Regardless of average level, the curves from all arrays display a sinusoidal nature that is characteristic of the amplitude-cycling nature of this chorus, with periodic changes in level of plus and minus a few decibels during this time.

The spectral density also was integrated over 100-Hz sub-bands covering the 300-800 Hz band to verify that the variability in level in all sub-bands had the same temporal dependence, and thus likely to be generated simultaneously from the same source(s). All sub-bands in which the chorus sounds were the dominant contributor showed the same temporal dependence in spectral level.

In summary, the short-term characteristics of these choruses can be summarized by four parameters: the frequency band over which the spectral density is integrated, the mean received sound pressure level, the variability in sound pressure level, and the periodicity of the changes in received level.

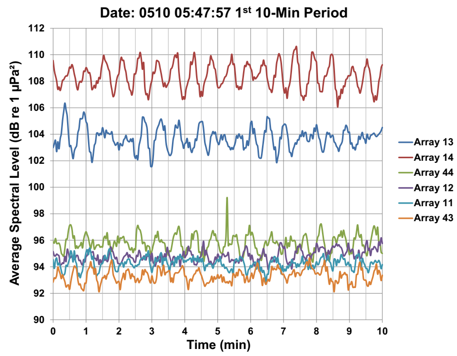

FIGURE 3: These 6 curves show the time series of the spectral levels obtained from integrating the spectrograms from a single element in each of the offshore arrays over the 300-600 Hz band. The 10-min time period on the horizontal axis is the same as in Fig. 2.

The longer-term temporal variability of the chorus, specifically, its diurnal variability, can be examined using the same processing approach as in the previous figure. The resulting sound pressure level time series over the 300-600 Hz band covering a full 24-hour period for the three arrays nearest to shore (Arrays 13, 14, and 44, in order from upcoast to downcoast) are shown in Fig. 4. Starting in the late afternoon, the sound levels begin to increase, reaching a sharp peak around local sunset. The short-term variability in level around the time of this "sunset chorus" is quite small (since the width of the curves is narrow), indicating that the chorus levels are not cycling in amplitude during this time. After this burst in sound production of several minutes duration, the levels decrease rapidly by 6 dB or so as the short-term variability (the width of the curves) increases due to the onset of the periodic cycling in level. The chorus continues all night long, with a slow decrease in average level of a few decibels, until around the time of local sunrise at which time the chorus rapidly disappears. It is replaced by large, short-duration spikes in level due mostly to coastal ship traffic, superimposed on a background level 10-20 dB below the nighttime chorus levels. The difference in chorus levels at the three array sites is related to the distance of each array from the regions of chorusing. Given that these chorus levels have a somewhat different temporal dependence over the course of the evening, it suggests either that the region of chorusing may be moving, or that the received levels at each array are dominated by the sounds generated in different regions. The latter appears to be the case from the beamforming results presented below.

Examination of the results from other days in May, 1999, indicates that, although the sunset chorus occurs within an hour or so of sunset, its actual correspondence with the local sunset time varies from day to day. This observation also holds true for the correspondence between the time of the sudden disappearance of the chorus and the time of local sunrise.

Longer-term variations in the chorus properties have been examined by comparing plots similar to Fig. 4 that were created from data recorded on days separated by over 1 month. The chorus begins to be clearly discernible on single element spectrograms recorded by the two shallow water inshore arrays, nos. 13 and 14, starting in mid April. The levels continue to increase up to the end of the data recording period.

In addition to measuring the spatial variability over a wide geographical area on a month-plus time scale, the major benefit of this 1999 data set in the study of this biological chorus is providing high spatial resolution estimates of the directionality of the sounds over

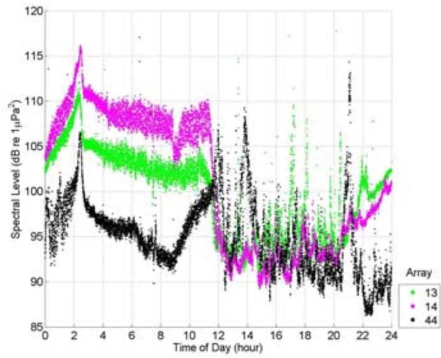

FIGURE 4: These 3 scatterplots show the 300-600 Hz integrated spectral level time series over the full 24-hour period on 10 May, 1999 (5 pm local, 9 May to 5 am local, 10 May). Only the data from single elements in the 3 inshore arrays (nos. 13, 14, and 44) are plotted for clarity.

time. The final figure, Fig. 5 below, shows the outputs using a robust adaptive beamformer (a white-noise-constrained adaptive beamformer having a constraint value 3 dB down from conventional) with the data from 5 elements in each of the 6 arrays in Fig. 1. Each plot covers a 13-hour period encompassing nighttime on the same day in mid May as in Fig. 4. Proceeding left to right in the upper row of Fig. 5 (from upcoast to downcoast for the arrays closest to shore), the predominant direction of the chorus suggested by Array 13 is 90-120 deg T, to the east-southeast towards shallower water and the coast (ruling out the ambiguous direction to the south). This directionality is remarkably constant over the 11-hour period. A secondary chorusing region starts to the north-northeast and evolves in the downcoast direction over 3-4 hours before disappearing. At Array 14 (middle plot in the upper row), the chorusing region appears to span a wide range of directions from north to south, with the highest levels coming from the northeast (excluding the ambiguous directions towards the northwest). A gap in received level occurs around 125 deg T. For the final inshore array (Array 44 in the upper right plot), the results suggest two chorusing regions, a primary one to the east, or possibly southeast, and a secondary one to the northwest towards the broad shallow-water shelf off Camp Pendleton. Around hour 11 (daybreak), a ship directly towards shore appears to start a transit upcoast at about 10 kt to a bearing of 330 deg T (-30 deg T), and then returns.

The results for the northernmost 2 offshore arrays show that the direction of the chorusing region appears to move in a counter-clockwise direction, from the southeast to the east and northeast, as the array location moves to the southeast. Interpretation of the results from these arrays is somewhat complicated by the apparent presence of sound sources independent of the sources of the biological chorus. However, this evolution in directionality with change in array location is consistent with the inshore array results presented in the previous paragraph. The results from the southernmost offshore array are anomalous, indicating either a completely separate chorusing region to the south-southeast or possibly an error in the array processing.

The beamforming results from the data recorded over the few other nights examined to date are remarkably consistent with those in Fig. 5, with the directions of chorusing changing by only 10-30 deg. Future work will examine potential changes in these chorusing directions in greater detail.

DISCUSSION AND CONCLUSIONS

The results presented in this paper represent an initial examination of the temporal, spatial, and directional variability of an underwater biological chorus in the nearshore regions

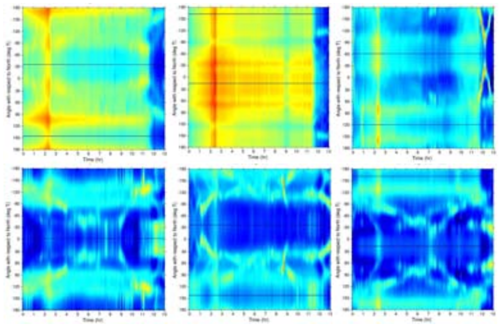

FIGURE 5: This figure show the 6 plots obtained from white-noise-constrained adaptive beamforming with the data from 5 elements of the mid-frequency subarray of each of the offshore arrays in Fig. 1, and integrating the output over the 300-500 Hz band. The plots are arranged so that those from the 3 arrays closest to the coast appear in the upper row, and those from the 3 offshore arrays occur in the lower row, with left to right in the figure corresponding to upcoast to downcoast. The time (horizontal) axis covers the 13-hour period from 00:00 Z to 13:00 Z (i.e., the night-time period from local 5 pm to 6 am) on 10 May, 1999. The beamforming output for each array has been rotated into absolute space, with a left-right ambiguity, using that array's line-of-bearing, where -180 deg (at the top of each plot) is due south, 0 deg (middle of each plot) is due north, and +180 deg (bottom of each plot) is due south. The original beamformer output with respect to array endfire is delineated by the two horizontal dark blue lines in each plot. The color-scale is the same for all plots and ranges from 70 (dark blue) to 110 (bright red) dB re 1 μPa^2.

off the southern California coast. The chorus occurs at night, following a sharp rise in levels for several minutes around sunset (the "sunset chorus"), and disappearing rapidly around local sunrise. The received levels are highest at the two shallow water inshore arrays, Arrays 14 and 13, making the fish entrapment records at SONGS particularly relevant. Based on abundance, the SONGS records (Miller *et al.*, 2011) suggest that queenfish is one of the species of southern California sciaenids participating in the nighttime chorus, with possible contributions from white croaker. The directionality of the chorusing regions is generally inshore from the array locations (after eliminating the ambiguous bearings in the westerly direction), with little change in directionality over the course of the night.

A numerical model has been developed that, with certain parameter settings, predicts the periodic cycling in level of this biological chorus. Specific changes in the model parameters cause a change to a modeled chorus with a time-independent received level, such as that observed during the "sunset chorus". An interesting question is whether or not these parameter settings can be related to behavioral and/or physiological characteristics of the fish(es) themselves.

Several studies have pointed to the significant decline in fish populations in the southern California Bight over the past few decades, e.g., (Roemmich and McGowan, 1995; Allen *et al.*, 2003; Miller *et al.*, 2011). Major sources of information for these studies are the records of fish entrapped at power plant intake structures along the southern California coast. The leading cause of the decline is attributed to the general warming and increased stratification of the waters in the southern California Bight. A second useful question is whether or not underwater passive acoustic measurements of the levels and other characteristics of this nighttime biological chorus can provide a measure of the abundance of the nearshore fish(es) creating the chorus. In any case, these studies and the results presented in this paper suggest that climate change, along with recreational and commercial fishing, may be leading to a decrease in nighttime ocean sound levels off the southern California coast.

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We dedicate this paper to the memory of Lewis P. Berger, who performed much of the original analysis of these fish choruses using data from the 1995 experiment. Several other individuals have collaborated over the years on the analysis of these biological choruses, including Joe Rice, Tony Richardson, and Jim Murray. Useful conversations have been held with Tom Norris, who hypothesized that the periodicity in the received level of these fish choruses coincides with that of breaking surf. Jerry Clapp of SPAWAR SSC Pacific provided the first description (as far as we know) of these "carpenter fish" sounds in a Navy Electronics Laboratory technical memorandum. David Horwitt and Bruce Thayre helped with the initial data processing of the array data, and Jason Ramsey contributed to reformatting the data onto LTO-4 tapes. Special thanks go to John Curtis of SPAWAR PMS-485 for his assistance with this data set.

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