Spectral Changes in Snapping Shrimp Sounds between Dusk and Dawn

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I. INTRODUCTION

Snapping shrimp sounds are a significant component of the ambient noise background in subtropical regions including Hawaii [1]. Quantification of this noise source is important to a variety of underwater acoustic applications, especially passive acoustic monitoring of harbors and ports. Previous studies have investigated shrimp noise in both laboratory and field settings [2-6]. The snapping shrimp sound production mechanism has been shown to be a result of a cavitation bubble produced by a high speed water jet originating from the closing of the claw [7]. Field studies have reported the spectra of ambient noise dominated by snapping shrimp in a variety of locations from data sampled at intervals on the order of hours to days. The snapping shrimp spectra has been shown depend on the season and phase of the moon [8]. A recent study in which sounds were recorded at 15 minute intervals reported increased RMS pressure levels during the daily sunset period followed by a plateau with a subsequent decrease during sunrise [9]. The corresponding spectral characteristics during such short time intervals have not been investigated previously. Moreover, background noise level changes on the order of minutes are of significant interest to passive acoustic security applications in which threat activity may have a similar time scale. Another emerging application of passive acoustics is the continuous monitoring of marine protected areas and wildlife sanctuaries. A goal of this is to detect and discriminate any boat activity with respect to the ambient noise background solely from long term acoustic time series records. We investigate the use of recurrence plots, an analysis originating from nonlinear dynamics for this purpose.

II. METHODS AND RESULTS

Ambient noise with snapping shrimp sounds were recorded in real time over several diurnal cycles at two sites in Oahu, Hawaii. At the Kilo Nalu Ocean Observatory (Oahu, HI), ambient noise was recorded over ten days with a 24 channel array (High Tech, Inc, Gulf Port, MS) with 102.4 kHz sampling. All 24 elements of the array were used during the daytime, while two were active at night. The observatory's ten meter power node, indicated by the red dot in Figure 1a allowed for continuous recording.

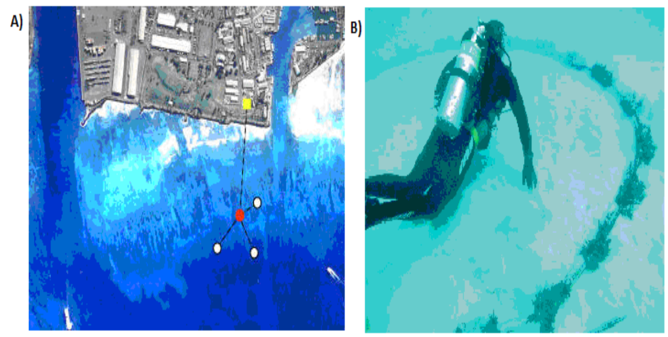

Figure 1. A) The Kilo Nalu Ocean Observatory (Oahu, Hawaii), one kilometer from Honolulu Harbor, was the site of one deployment. The Kilo Nalu power nodes are shown by the red and white circles B) A diver deploys the hydrophone array on the seabed.

Figure 2 displays the recorded RMS pressure levels recorded showing the diurnal variations during the sunset and sunrise periods. A sharp rise in the SPL occurs during the sunset period, followed by an overnight plateau and a subsequent decrease during sunrise. This is similar to the results reported by Lammers et al for Kaneohe Bay [9]. In that study, a single hydrophone acoustic EAR system was used with a sampling rate of 25 kHz. The EAR recorded data for 30 seconds every 15 minutes. In our study, we continuously sampled at 102.4 kHz, with a time resolution and sampling rate comparable to snapping shrimp activity [6,7].

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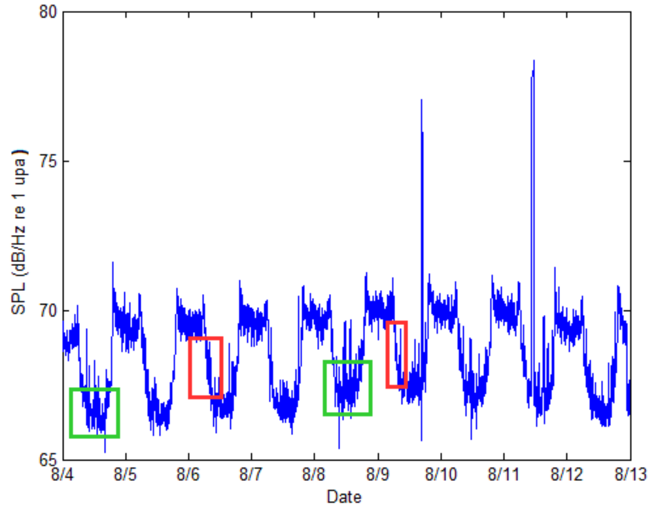

Figure 2. Root mean square (RMS) SPL levels (Kilo-Nalu, Oahu, HI) show a sharp rise during the sunset period followed by a plateau and a decrease. The spikes during 8/9 and 8/10 are attributed to scuba activity near the array. The colored boxes indicate segments of the time series used in the analysis.

Snapping shrimp activity has been related to sunlight [8,9]. In Figure 3, the RMS SPL levels for August 8th were plotted with the corresponding sun irradiance data taken from the National Renewable Energy Laboratory [10]. The inverse light intensity corresponds to the RMS SPL levels. Similar results were found for other days of the deployment.

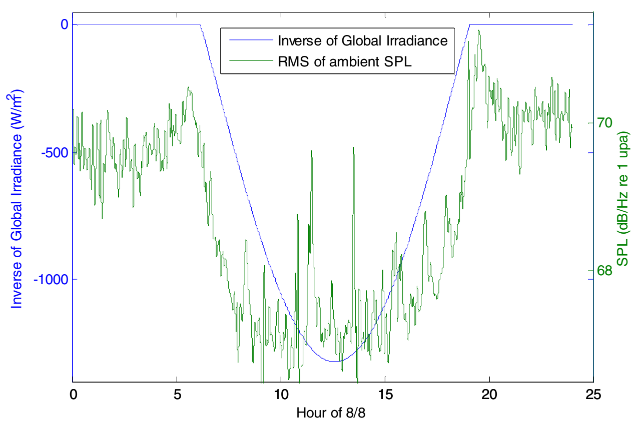

Figure 3. The ambient sound levels plotted against the inverse of sunlight intensity. The peaks in ambient sound occur 20 minutes before sunrise and 20 minutes after sunset.

Figure 4 shows the spectral changes during the sunrise period of August 6 for three time points. Spectra are shown for three time points starting at 5:30 AM in 45 minute intervals. The frequency content as well as overall noise level change during this time interval. In particular, the lower frequency peak centered at 3.5 kHz decreases by over 6 dB and the higher broadband peak centered about 12 kHz decreases by 3 dB. Corresponding increases in the spectral levels were observed during sunset.

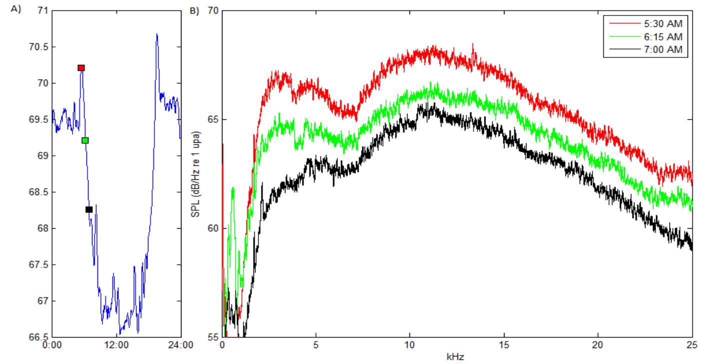

Figure 4. A) The ambient noise RMS levels on August 6. B) The frequency spectra of the raw acoustic signal at three points corresponding to a decrease in the SPL levels during the progression of the sunrise.

Figure 5 shows spectra computed over three different time windows. We took the average spectra for a one week time period, two and a half hours during sunset, and 30 seconds near the peak SPL level at sunset. The 30 second spectrum shows the highest ambient noise SPL level. The one week average was 4.5 dB lower for the 4 kHz peak and 3 dB lower for the 8 kHz peak.

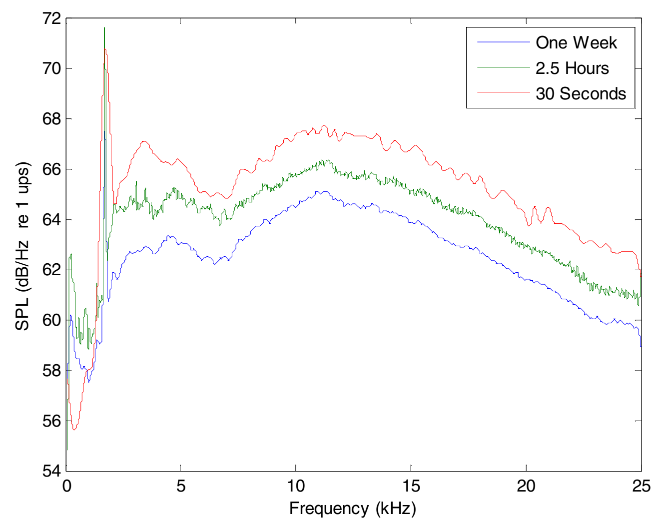

Figure 5. The spectra of ambient noise averaged over three time windows. The continuous sampling at 102.4 kHz allows for the shorter time scale computations at 30 seconds.

Snapping shrimp sounds have been reported to vary depending on geographic location on Oahu [1,6,9]. Ambient sounds were recorded with a calibrated single hydrophone (Reson TC4013, Reson Inc., Goleta, CA) over a 24 hour period with 50 kHz sampling at the Hawaii Marine Mammal Lab, Coconut Island, Oahu, HI, on the windward side of Oahu. This location is in Kaneohe Bay, as shown in Figure 6. Kaneohe Bay and Coconut Island are active sites for research on coral reefs and shrimp habitats [6,9].

Figure 6. Aerial view of Coconut Island (Google Earth), the location of the Hawaii Institute of Marine Biology (HIMB) and the associated Hawaii Marine Mammal Lab. The red dot indicates the location of acoustic data collection.

The spectra over a four hour period during sunset on June 15 for this site are shown in Figure 7. The lower frequency peak centered at 4 kHz increases by 5.5 dB, and the broadband peak centered at 8 kHz increases by 3.5 dB. In this case, the 4 kHz peak is significantly higher than the 8 kHz peak.

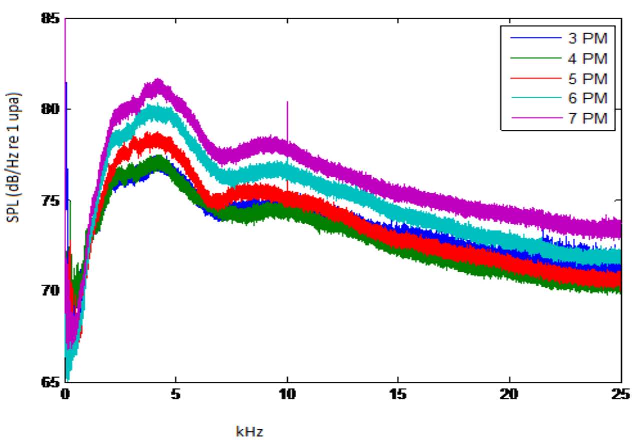

Figure 7. Ambient noise spectra (June 15, Coconut Island, Oahu, HI) of snapping shrimp show an increase in level during a four hour time interval of the sunset period.

In a complimentary study on the detection of ship signatures subject to ambient noise, ambient data was collected with the 24 channel hydrophone array (102.4 kHz sampling) at the same Coconut Island location. This data was taken over three days between 10 am and 4 pm. The acoustic signatures of the shuttle boat were investigated. At Coconut Island, this shuttle boat runs frequently between the island and the shore to transport personnel and supplies. The HIMB shuttle boat (Figure 8) is a 17 foot Boston Whaler with a 40 horsepower Honda engine.

Figure 8. The Hawaii Institute of Marine Biology's shuttle boat. Its acoustic signature was recorded by the hydrophone array between 10 am and 4 pm (6/26-6/28)

A GPS tracking device was placed on the shuttle boat with a sampling rate at 1 sample per second to ground truth its location. Complimentary time synchronized acoustic and photographic data were obtained to monitor the boat activity. Figure 9 shows two sample GPS tracks of the shuttle boat traversing from the island to the shore.

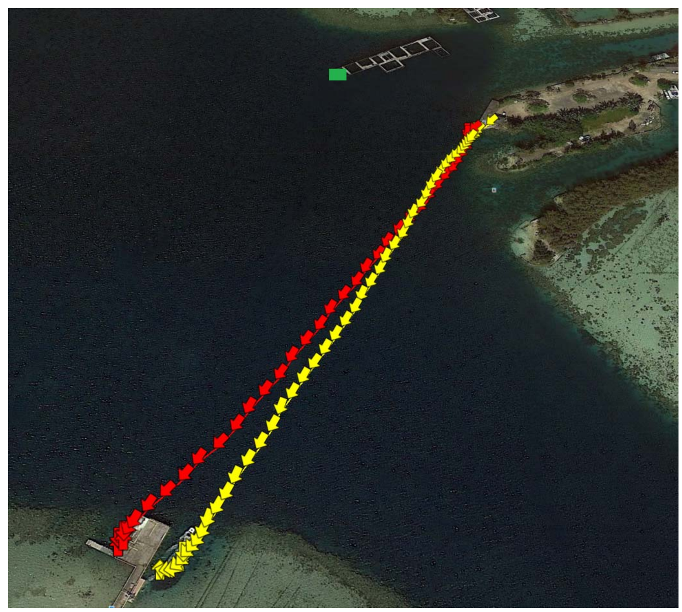

Figure 9. Two GPS tracks of the boat leaving Coconut Island for the shore. The red indicates the first pass at 10:50, and the yellow follows the boat's second pass at 11:16. The green square indicates the position of the hydrophone array..

III. ANALYSIS AND DISCUSSION

Previous studies have investigated snapping shrimp acoustics in terms of the spectra, number of individual types of signals such as snaps, and spatial distributions of the sound [1-9,11]. Nonlinear time series analysis of the sounds has not been investigated previously. Nonlinear time series analysis of such acoustic data can be obtained with recurrence plots. Recurrence plots are a method introduced in 1987 by Eckman [12] for the study of nonlinear dynamical systems. Recurrence plots provide a method of visualizing the recurrence of nonlinear, nonstationary systems in phase space. This is achieved by a reconstruction the phase space of a system using a single time series through a time delay embedding [13]. A recurrence plot determines times in which that phase space returns within specific criteria to a previous state. This analysis has been used to detect physiological irregularities from times series [14] and to study geophysical processes [15]. The time series is embedded into a phase space with an appropriate embedding dimension determined by the false nearest neighbors method and an appropriate embedding time delay obtained from the mutual information. A time-time plot is obtained for instances in which the system recurs to a previous state in its phase space as described below [16]:

$$R_{i,j} = \{1: x_i \approx x_j ; 0: x_i \neq x_j , j=1,\ldots, N \qquad (1)$$

The plot provides both visual information and also various dynamical invariants of the system can be determined. We use software in the recurrence plot toolbox developed by Marwan et al. [17] from which dynamical invariants such as entropy, determinism, laminarity, and recurrence period density entropy can be obtained.

Shown in Figure 10 is the recurrence plot of the RMS values of the Kilo Nalu data (Figure 2). The signal's nonstationary characteristics are indicated by the paling of the line intensity towards the corners. This can be quantified through the recurrence plot measure of the trend, which is -.745. The trend is a measure of the stationarity of the recurrence plot, and corresponds to the amount of paling near the edges. The determinism is a measure of the percentage of points which fall into diagonal lines, and gives insight into the predictability of the system. Strong periodicity is visible in the distinctive diagonal lines and corresponds to a determinism value of .997. The red box indicates the segment of the recurrence plot which relates the two sunrise periods indicated by the red boxes in Figure 2. The green box indicates the section of the recurrence plot which compares the two midday periods indicated by the green box in Figure 2. The red box has a significantly higher rate of recurrence, noted by the greater intensity. This indicates that the two sunrise periods are more similar than the two midday periods.

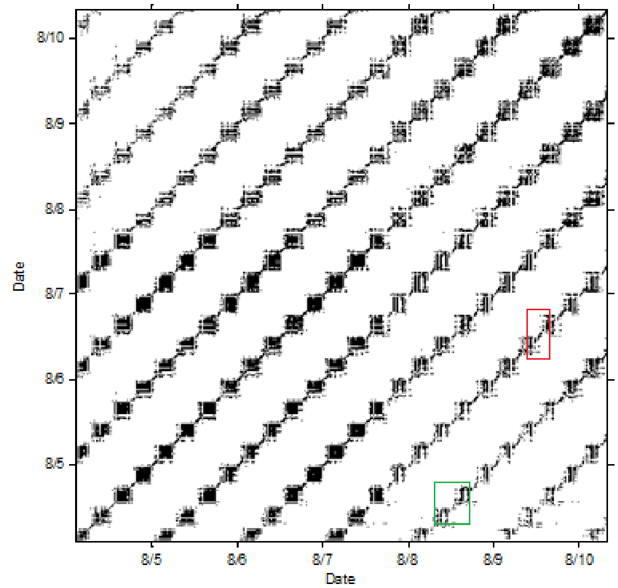

Figure 10. Recurrence plot of RMS SPL over the one week period shown in Figure 2. The colored boxes indicate time segments of the plot which correspond to those highlighted in Figure 2.

Other dynamical invariants of interest can be obtained from the recurrence plot. In general, these are known as recurrence quantification analysis (RQA) measurements and have been used more extensively in recent studies [14-16]. One such measure is the laminarity, which measures the percentage of points which fall into vertical lines, and is related to the intermittency of the system. The Shannon entropy is calculated from the distribution of diagonal lines in the recurrence plot. This is a measure of the amount of information in the signal. Recurrence period density entropy (RPDE) is a measure of the repetitiveness of the system. We determined these quantities for acoustic data sampled for three seconds every thirty minutes over the sunset period. These results are shown in Figure 11. We note these RQA measures have little relative change over this time period.

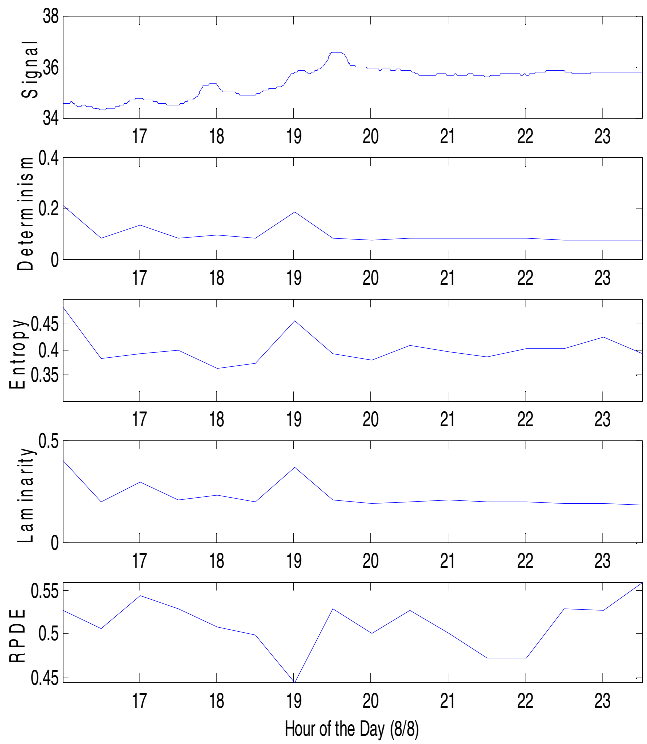

Figure 11. The top panel shows the RMS level of the SPL. The panels below show the corresponding RQA quantities found from the corresponding raw acoustic data during this sunset period.

One potential application of recurrence plots is to detect transient or anomalous events. It has been used to find such events within signals such as EKGs [14] in biomedical applications and geological time series [16].

We investigate detecting boat activity relative to the ambient snapping shrimp background. By examining times in the plot with very low recurrence, acoustic signatures of boats were detected which were verified with the optical records. This is shown in Figures 12 and 13. Figure 12 shows the recurrence plot of one hour of data (June 26), in which the shuttle boat completes five round trips. For these trips, we know the location of the boat through GPS. For two of the passes, marked in red in Figure 12, the presence of a boat is apparent in the time series as there are peaks in the RMS time series over the ambient levels. These peaks create significant white bands (periods of low recurrence) in the recurrence plot, indicating an event which is not repeated throughout the time series. These peaks correspond to the boat coming within five meters of the hydrophone array. A third pass, marked in blue, is noticeable but difficult to distinguish from the background. The recurrence plot facilitates detection in the time series, as there is a visible white band at this time in the recurrence plot. The two boxes marked in green are known shuttle boat activity; however these are even more difficult to discern through either the RMS values of the data or the raw acoustic data.

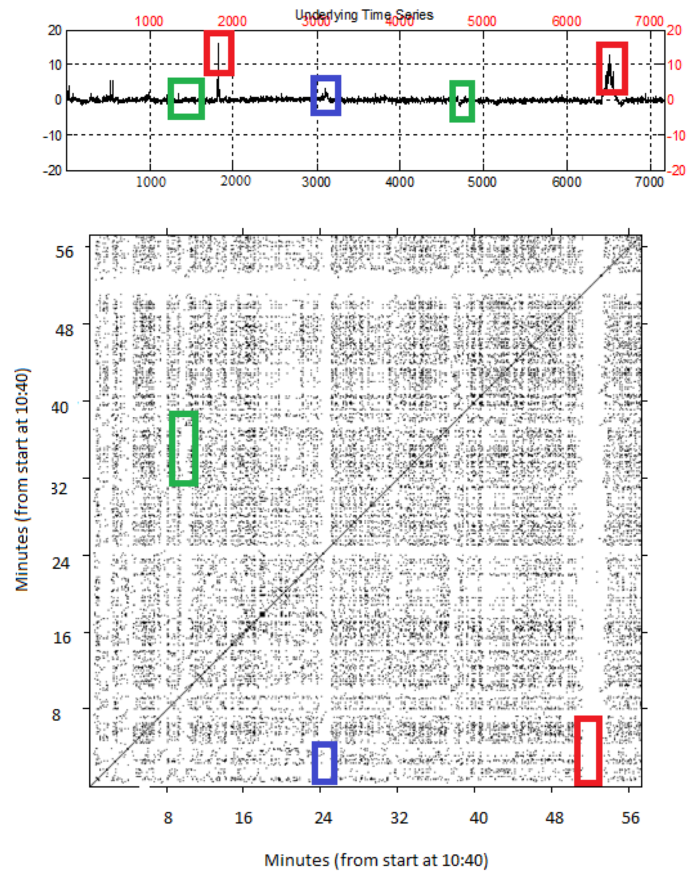

Figure 12. Recurrence plot of the RMS values of one hour (10:40 am to 11:40 am) at Coconut boat data (6/26), taken from one hydrophone of the array at ~4 meters of depth. The RMS values are obtained at two samples per second.

Figure 13 shows the green box area of the recurrence plot in Figure 12 in greater detail. It displays a shorter time frame for a recurrence plot which compares the signal from the first boat pass with the signal from the fourth boat pass. A white band is visible for the first boat pass, indicating that there is an unusual event there relative to the background noise. In addition, the signal of the fourth boat pass is found to recur with the signal of the first boat pass. This indicates that the two signals are similar enough to be within the recurrence criteria as given by (1). This result suggests recurrence plots may aid in the detection of boat activity in a robust manner with less computational complexity than current methods [18,19].

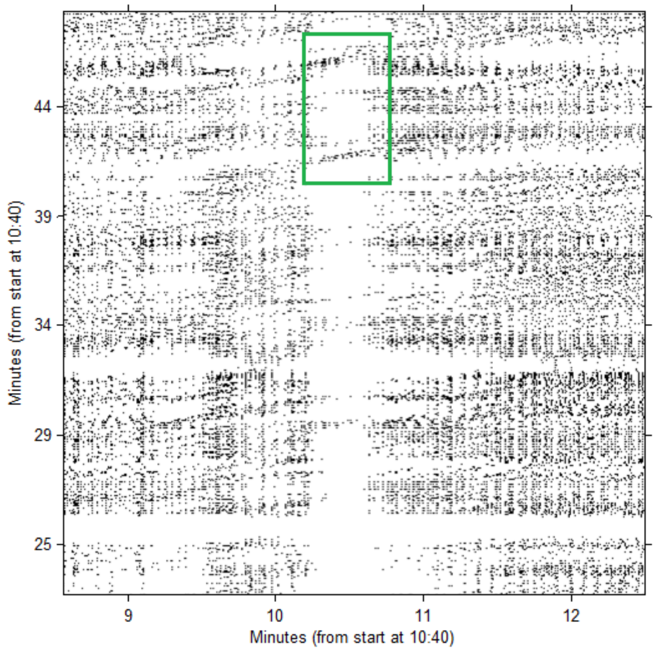

Figure 13. The recurrence plot for the time interval between the first and fourth boat pass. The green box indicates the exact time segment during which the two boat pass signals coincide.

IV. Conclusion

We report continuous time acoustic recordings of snapping shrimp dominated ambient noise at two shallow water locations on Oahu, Hawaii: Kilo Nalu Observatory and Coconut Island. We are able to resolve novel spectral changes in the ambient noise during sunrise and sunset by using higher sampling rates than have been previously employed. Also, we show that there is a significant difference in spectral levels depending on the time window used in its calculation. Spectral levels calculated over a time scale on the order of seconds to minutes can be different on the order of ~3-6 dB from those calculated over a week. This is important for harbor security applications in which potential events of interest may occur on the scale of minutes. Previously reported ambient noise spectra averaged over the course of a week or more may not be appropriate for these scenarios and likewise the design of acoustic harbor security systems.

We investigate the use of recurrence plots to quantify snapping shrimp dominated ambient noise. Furthermore, we examine the use of recurrence plots to find novel events relative to the ambient noise background. In particular, we show that the acoustic activity of the HIMB shuttle boat can be detected with a recurrence plot. We hypothesize that recurrence plots have the potential to detect boat activity in noisy shallow water environments. In addition, recurrence plots may be able to discern repeated boat patterns and paths. This may be useful for the passive acoustic monitoring of reoccurring illegal fishing in marine protected environments.

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