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WESLEY LYLE GOODE for the M. Oc. E.
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Title: AN INVESTIGATION OF THE ACOUSTIC SIGNATURE OF THE DUNGENESS CRAB (Cancer magister)

Abstract approved: Signature redacted for privacy.
L. J. Jensen

The acoustic signals produced by the Dungeness crab (Cancer magister) were investigated. The signals were examined for duration times and frequency content. The signals were converted from analog to digital form, and the autocorrelation functions and the power density spectrums were determined.

The signals produced by Dungeness and Japanese red rock crabs were found to last from 2.8 to 30.0 milliseconds. The frequencies contained in these signals ranged from 800 to 15000 hertz, the pass-band of the filter used in the signal recording process. The autocorrelation functions were found to possess either a decaying sinusoidal wave shape or a sinusoidal wave shape displaying a nodal and anti-nodal characteristic. Nodal and anti-nodal behavior was found in 65% of the male Dungeness crab signals, and in 25% of the female Dungeness crab signals. The time period between nodes in the autocorrelation functions of signals produced by Dungeness crabs was

generally found to be less than two milliseconds. The time period between nodes in autocorrelation functions of signals produced by a related species, the Japanese red rock crab, was generally found to be four milliseconds. The power contained in a signal was found to be concentrated in a narrow band of frequencies in a majority of the signals. The frequency containing the maximum power of the signal was found to be between 4000 hertz and 6000 hertz in 69% of the large Dungeness male signals. The Dungeness female signals contained maximum power frequencies in this range in only 35% of the signals, with a significant percentage, 30%, of the maximum power frequencies occurring below 2000 hertz.

An Investigation of the Acoustic Signature of the Dungeness Crab (*Cancer magister*)

by

Wesley Lyle Goode

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APPROVED:

Signature redacted for privacy.

Associate Professor of Electrical and Electronics Engineering
in charge of major

Signature redacted for privacy.

Head of Department of Electrical and Electronics Engineering

Signature redacted for privacy.

Dean of Graduate School

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Typed by Opal Grossnicklaus for Wesley Lyle Goode

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AN INVESTIGATION OF THE ACOUSTIC SIGNATURE OF THE DUNGENESS CRAB (Cancer magister)

I. INTRODUCTION

The decapod crustacean Cancer magister is found only on the western coast of the North American continent. It ranges from Magdalena Bay in Baja California, Mexico to Northwestern Alaska (Pruter, 1966). The factor which determines the limits of this range seems to be the surface water temperature. The northern boundary coincides with a temperature of 40 degrees Fahrenheit, and the southern limit with a temperature of 75 degrees Fahrenheit (MacKay, 1943). These crabs inhabit shallow water and do not range beyond the continental shelf. This information is shown in a pictorial form in Figure 1.

Cancer magister, like most animals with Latin scientific names, also has a common name. The fishing industry for this crab started in Dungeness (pronounced Dun'-jen-ess) Washington, and the crab inherited the name of the town (Rees, 1963). Cancer magister will be referred to by its common name throughout the rest of this report.

The commercial fishing for Dungeness crabs has developed into an economically important industry in the Northwestern United States. Investigations of the life cycle, breeding habits, physiology, migrations, feeding habits, and distribution of these crabs have been extensive. There is no known published work on sounds emitted by the

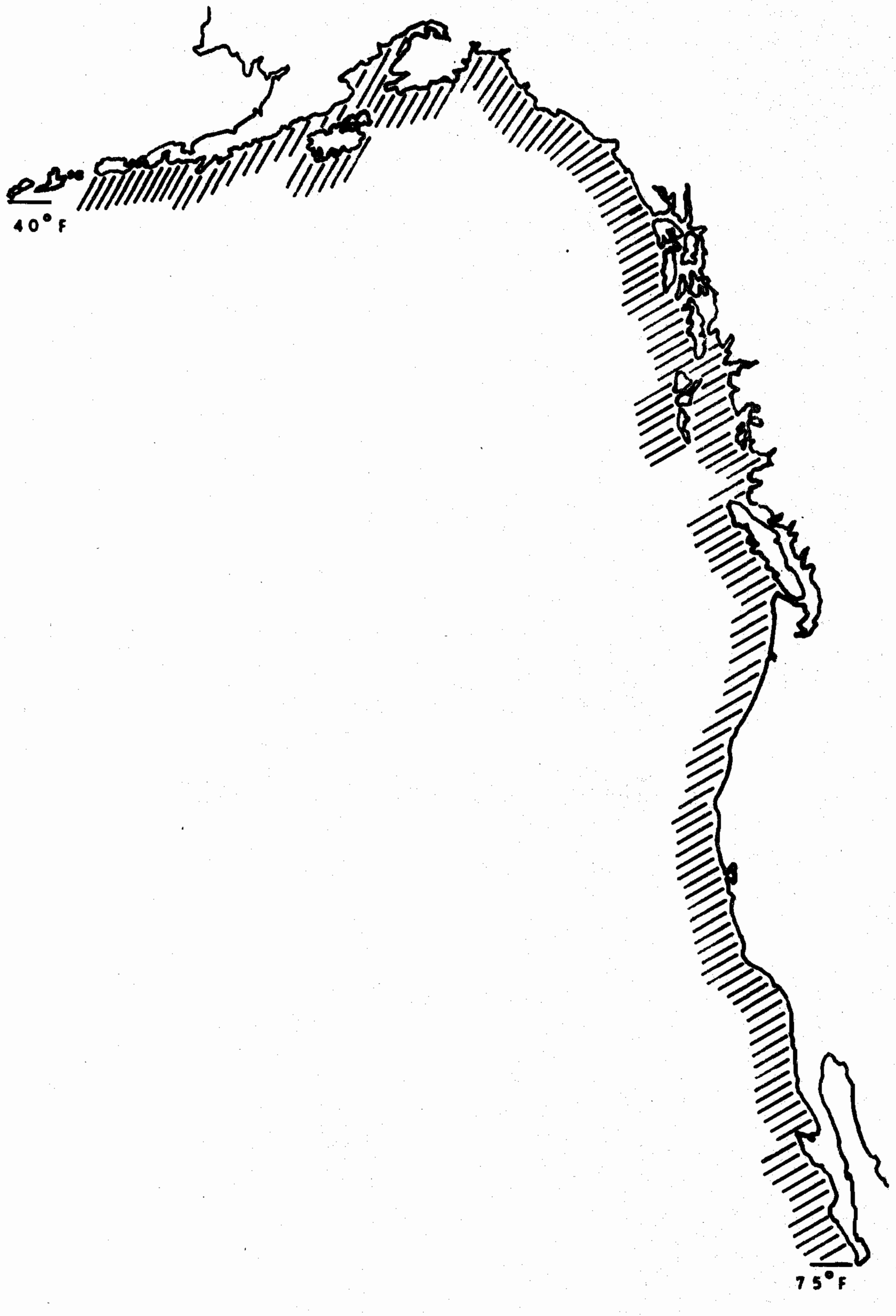


Figure 1. Distribution of Cancer magister.

Dungeness crab, or on its acoustic signature.

The purpose of this investigation is to determine if identification of the Dungeness crab is possible by examining the acoustical signals it produces. Signals recorded from crabs that were isolated and were identified as to size, sex, and species are analyzed. The analysis included the duration time of the signal, frequency content, autocorrelation function, and power density spectrum. The results of the analysis are compared to determine if any characteristics exist which might identify the species, size, or sex of the crab which produced the signal.

II. BACKGROUND INFORMATION

The sea has often been referred to by man, as "The silent world." It has been recognized for years that marine animals produce sounds, and some sounds produced by fish were described by Aristotle and Pliny centuries ago (Tavolga, 1964). Still, the idea of the sea being relatively quiet was a common one. Not until the advent of transducers capable of detecting underwater sounds was this notion dispelled forever. It now appears that, of the more than 20,000 known species of fish, a large percentage are capable of producing some type of sound. Most of the warm-blooded aquatic mammals: the porpoises; dolphins; seals; whales; etc., produce detectable sounds. Many forms of marine invertebrates are also sound producers, the principal sonic forms being the crustaceans (Tavolga, 1967). Sound production in decapod crustaceans was recognized almost a hundred years ago (Kent, 1877).

An insight into the nature of the sounds produced by marine invertebrates can be gained by examining the problems faced by these organisms in attempting to produce a signal that is useful for communication. Marine invertebrates live in a relatively dense medium which requires a greater expenditure of energy for movement than does air. The ambient noise level in the surrounding environment is relatively high and is composed of broad-band sounds.

To communicate in such an environment, the invertebrate must produce a sound which has a fairly high intensity. This can more readily be accomplished if the signals are of short duration. The signals must also be very sharply structured, composed of rapidly increasing and decaying periods. In crustacea the conditions of a short, high intensity signal composed of transients, are met by producing a snapping or a rasping sound (Frings, 1964). Tavolga (1967) described the basic sound produced by invertebrates as a "click." This is a short pulse of noise, lasting about one millisecond, and containing frequencies throughout the entire audible spectrum (20-20,000 hertz).

The method of sound production in many members of the higher crustaceans is by stridulation, i.e.--the rubbing of parts of the exoskeleon together, or by the snapping of their claws (Nicol, 1960). Many of the crustaceans possess special stridulating mechanisms with which they produce sounds (Evans, 1968), and some decapod crustaceans are known to produce characteristic sounds using this method (Cohen and Dijkgraaf, 1961). The sounds produced by stridulation consist of a series of broad-band noise pulses (Tavolga, 1967).

The question of whether or not the sounds produced by crustaceans are purposeful or accidental is not fully resolved. The stridulatory sounds may be produced by accident when the animal moves, or the sounds may be produced to transmit some form of information. If information is contained in the signals, then it can be assumed that the organisms have some purpose for communicating with other animals. There are many obstacles which an animal must overcome if it is to survive. It must locate the right food supply, fend off danger and competition, and identify and locate the right mate. In a world that is vast and hostile, there is no room for error in any information, either transmitted or received (Evans, 1968).

If the crustaceans produce signals for the purpose of communication they should also be capable of receiving communications--especially from members of the same species. Marine crustaceans possess a variety of proprioceptors in their bodies and appendages. Many of these are known to be responsive to body or appendage movements of very slight magnitude. The known properties of these receptors indicate that they can detect the intensity and wave form of pressure waves. Crustaceans also possess various sensory hairs on the body surface that can detect water movement. These hairs might also act as sound detectors (Tavolga, 1967), however the amount of information on the hearing ability of crustaceans is small and Lockwood (1967) maintains that it is doubtful they can detect underwater sound waves.

While the sounds of marine organisms have been studied by marine biologists, the engineer can expect to find little information on what frequency content and intensity levels to expect in marine sounds (Urick, 1967). Some species have been studied more than other, and some quantitative data on sound production are available. Information on the snapping shrimp can be found in papers by Albers (1965), and Snodgrass (1968). Salmon (1967) has recorded data on the fiddler crabs, and Hazlett and Winn (1962) have investigated some of the crustaceans around Bermuda.

The limited amount of quantitative data is due, in part, to the equipment required for proper investigation of underwater sounds. "The sounds produced by marine invertebrates consist of transient pulses for which ordinary sound-recording equipment is poorly adapted" (Frings, 1964). Not until recently has suitable equipment been developed for studying underwater sounds.

III. METHODOLOGY

The investigation of the acoustic signature of the Dungeness crab involved two separate phases. The first phase consisted of obtaining Dungeness crabs for study, and recording the sounds they produced. The second phase involved analyzing these signals to determine their characteristics. The crab sounds were recorded at the Oregon State University Marine Science Center, located on Yaquina Bay, at Newport, Oregon.

Data Collection

Prior to the beginning of a recording session, live Dungeness and Japanese red rock crabs were caught in Yaquina Bay using baited crab rings. The crabs were then transported to the Marine Science Center and placed in a holding tank filled with water from the bay. An individual crab was taken from this tank and placed in a six foot diameter redwood tank, filled with bay water to a depth of approximately three feet. The crab was allowed to acclimate to this new environment before the sounds it produced were recorded.

The sounds produced by the crab were detected by a piezoelectric transducer suspended in the tank. The piezoelectric material produces a varying voltage signal at the output terminals of the transducer which is proportional to the varying pressures contained in an underwater sound. All underwater sounds occur in the form of such pressure variations. The transducer was placed about two feet from the side and one foot off the bottom of the tank. The specifications and characteristics of this transducer are shown in Appendix I.

The output of the transducer was amplified by a factor of 39 db. (about 100 times), before transmission by cable to the recording station 60 feet away. Pre-amplification increased the signal level so that any noise introduced during transmission was negligible with respect to the transmitted signal. At the recording station the signal was further amplified by a factor of 40 db. (100 times). This amplification raised the signal to the level which provided the maximum signal-to-noise ratio in the data recorder.

After amplification, the signal was filtered using a tunable band-pass filter. Filtering was necessary to eliminate the sounds being produced by the surrounding equipment at the Marine Science Center. These low frequency sounds were of sufficient amplitude to saturate the electronics of the data recorder. The lower cut-off frequency of the filter was set at 800 hertz in order to eliminate these unwanted sounds. The upper cut-off frequency of 15,000 hertz was determined from data recorded and analyzed to establish the upper frequency limit.

The crab signals from the transducer were monitored by displaying them on one channel of a dual channel oscilloscope. The recorded signals were displayed on the second channel of the oscilloscope. This provided a means of comparison to insure that the signals were being recorded without distortion.

The signals were recorded on one channel of a 14 channel Ampex data tape recorder. All recordings were made at a tape speed of 60 inches per second (hereafter referred to as ips.). After recording a sufficient number of signals from the crab, it was then placed into another tank separate from the other crabs. The process was then repeated with each crab, with its sounds being recorded on a separate channel of the recorder.

The sounds produced by *Cancer productus*, the Japanese red rock crab, were also recorded since this crab is a close relative of *Cancer magister*. If the sounds produced by the Dungeness crabs are characteristic it should be possible to distinguish between the sounds produced by each species. A total of 16 Dungeness and five Japanese red rock crabs were examined using this procedure.

The same equipment was placed on board the RB Paiute in order to record crab signals in the open bay. In this situation the transducer was attached to a baited crab ring and placed on the bottom of the bay. These bay signals were recorded to provide a means of comparison between those signals detected in open water, and the signals detected from isolated crabs under laboratory conditions.

Analysis Procedure

The analysis of the recorded crab signals was done in five steps. (1) The signals to be analyzed were selected. (2) The frequency content of the signals was determined. (3) The time varying signal (analog form) was converted into a series of discrete values (digital form). (4) The autocorrelation function of the signal was calculated. And (5) the power associated with each frequency (power density spectrum) was computed.

Signal Selection

The signals chosen for analysis were selected visually by viewing the wave shapes on an oscilloscope. A majority of these signals had a relatively short duration time (2-30 milliseconds). This made it necessary to time-expand the signals. A 1:4 time expansion was accomplished by playing the signals back from the recorder at a reduced speed of 15 ips. Five signals were selected which appeared to be characteristic of the signals found on a given channel. These five signals were then re-recorded on a blank channel reserved for this purpose. A total of 113 signals were selected for analysis. Eighty-three signals were from isolated, identified crabs and 30 signals were from the recordings made in the open bay.

The selected signals were then reproduced on a strip chart recorder. The strip charts were used to identify the proper signals in other phases of the analysis procedure. No significant quantitative results could be obtained on signal amplitude from these charts as the frequency response of the strip chart recorder was too low. The strip charts did provide quantitative data on the duration time of the signals.

Frequency Analysis

The signals selected for anlaysis were transferred from the data tape recorder to the Kay Spectrograph. The spectrograph re-recorded the signals on a rotating magnetic drum. The rotation of the drum caused the signal to repeat at regular intervals, thus forming a continuous signal out of a transient signal. The signal was analyzed by electronically sweeping a tunable filter through a pre-set frequency range. The band width of this filter was set at six hertz to achieve maximum resolution of the frequencies contained in the crab signal.

The signals were transferred from the recorder to the spectrograph manually. Manual switching was selected over electronic switching for two reasons. First, the magnitude of the spurious noise pulses present on the tape recordings was sufficient to activate any electronic circuit designed to turn on in the presence of a crab signal. Second, the switching time of mechanical relays in the spectograph would have caused a portion of the signal to be lost.

To facilitate manual switching it was necessary to incorporate a 1:32 time expansion. This was done by transferring the signals from the data recorder at a tape speed of 1 7/8 ips. As a result of the time expansion all frequencies present on the tape were reduced by a factor of 32:1. This changed the unfiltered frequency range of 800-15000 hertz to a range of 25-470 hertz. In order to be consistent with this lower range the spectrogram was set to analyze frequencies between 15-1500 hertz.

This range setting provided eight seconds of recording time on the spectrograph's magnetic drum. The individual crab signals, lasting a maximum of one second, were selected from the eight seconds of re-recorded signals. The spectrograph could have been set to record 0.8 seconds, however this did not provide enough time to manually switch the crab signal, record the crab signal, and manually switch a calibration signal onto the magnetic drum.

It was possible to change the frequency range of the spectrograph from 15-1500 hertz to 15-750 hertz, without changing the amount of recording time, by switching in a circuit designed for this purpose. This lower scale was selected for use since it would enlarge the frequency display and provide greater accuracy in reading the display.

A record of signal intensity vs. signal frequency at a given point in time can also be obtained from the spectrograph. This provides a measure of the signal strength at a given frequency with the same degree of resolution as the frequency vs. time display.

Sonograms, the graphic displays of frequency vs. time, obtained from signals produced by large male Dungeness crabs are shown in Figures 4, 5, and 6. Those obtained from small male Dungeness crabs are shown in Figures 7 and 8. Figures 9, 10, and 11 show sonagrams obtained from female Dungeness crabs. Sonograms of two unidentified bay signals are shown in Figures 12 and 13. The autocorrelation functions and the power density spectrums of these signals are shown in later figures. The sonogram, autocorrelation function, and power density spectrum of an individual signal can be located by consulting Table I, which contains the figure numbers for each signal.

Data Conversion

In order to perform the mathematical operations necessary to calculate the power density spectrum and the autocorrelation function, it was necessary to convert the signals to a digital form. This was done using a ESI-690 Hybrid computer. The analog signal was sampled at a pre-determined frequency, and the value of the analog signal at each sample point was stored in the computer.

The sampling frequency was made at least twice the highest frequency component contained in the analog signal, as determined by the frequency analysis. This complies with Shannon's sampling theorem for retaining all information contained in a signal prior to sampling (Elgerd, 1967). The use of a standard sampling frequency, as determined by twice the highest frequency found in any of the selected signals was not considered possible. The number of sample points for the longer, lower frequency signals would have exceeded the storage capacity of the computer. The sampling frequencies used, and the number of samples per cycle are shown in Table II.

The sampled signal stored in the computer memory bank was displayed on the computer's strip chart recorder. This display was compared with the strip chart obtained in the signal selection process to assure storage of the correct signal. The frequency response of the computer strip chart was such that quantitative data could be obtained only on the time duration of the signals.

The portion of the sampled signal which contained the desired crab signal was chosen by visual inspection of the computer strip chart display. All extraneous portions of the digital signal, i.e. -- noise, extra crab signals, and blank spaces, were excluded from the computer's memory bank. An example of a sampled signal reproduced on the computer strip chart and the area selected for storage is shown in Figure 2. The area within the dotted lines was

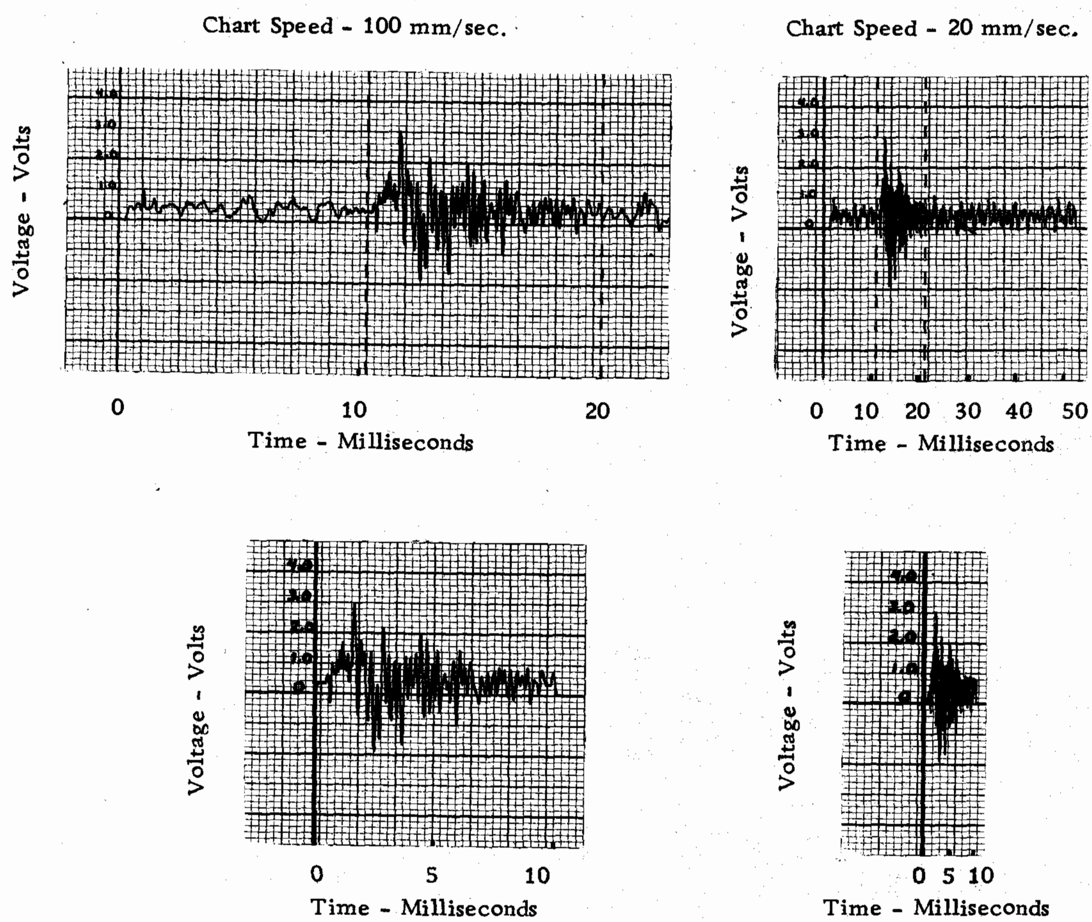
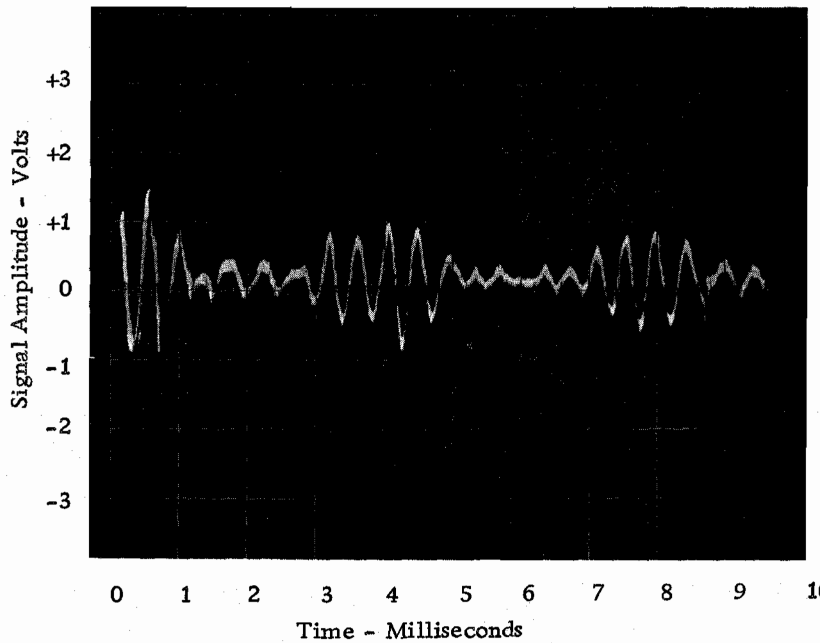


Figure 2. (Upper) Large male Dungeness crab signal selected for analysis.
(Lower) Large male Dungeness crab signal stored in the digital computer.



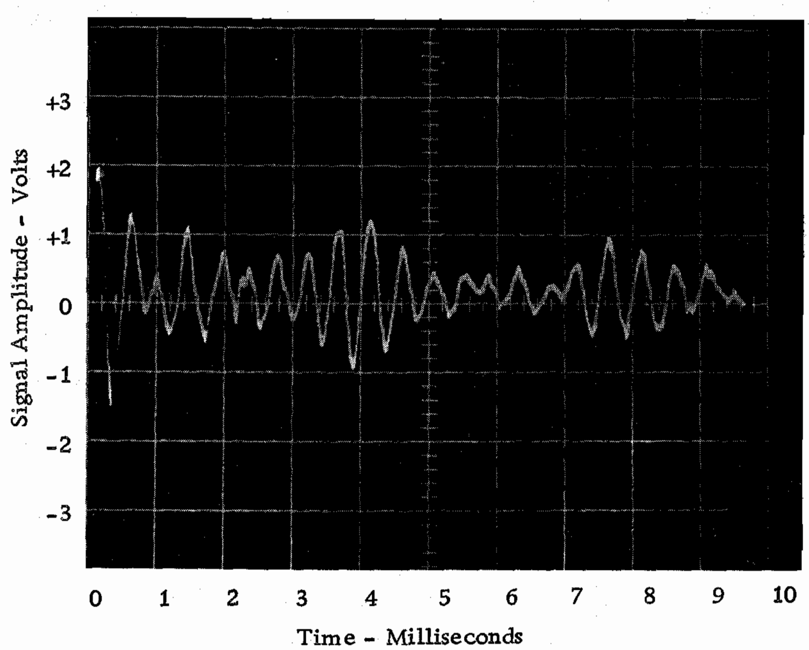
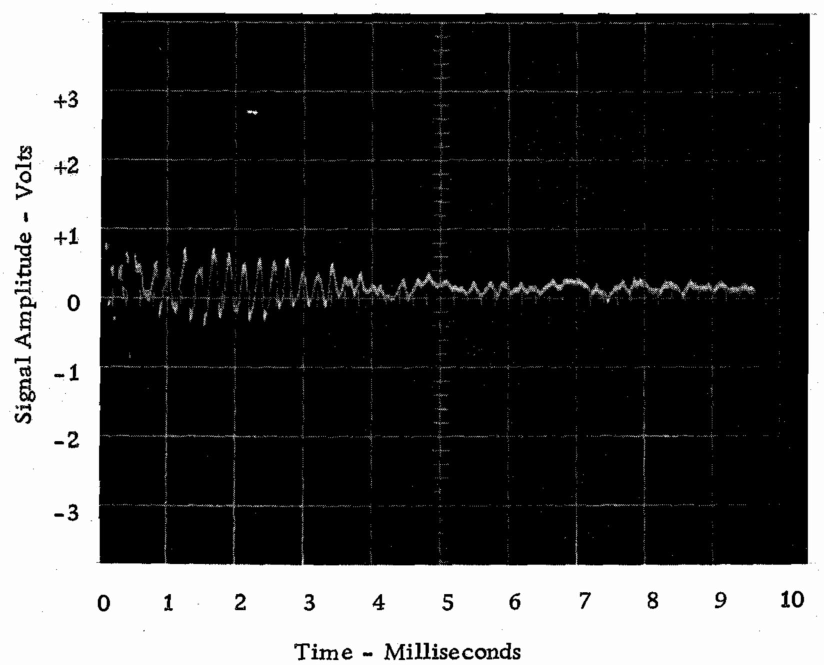


Figure 2b. Typical wave shapes of Dungeness crab signals. Supplemental data obtained after concluding the investigation (obtainable due to the arrival of new equipment).



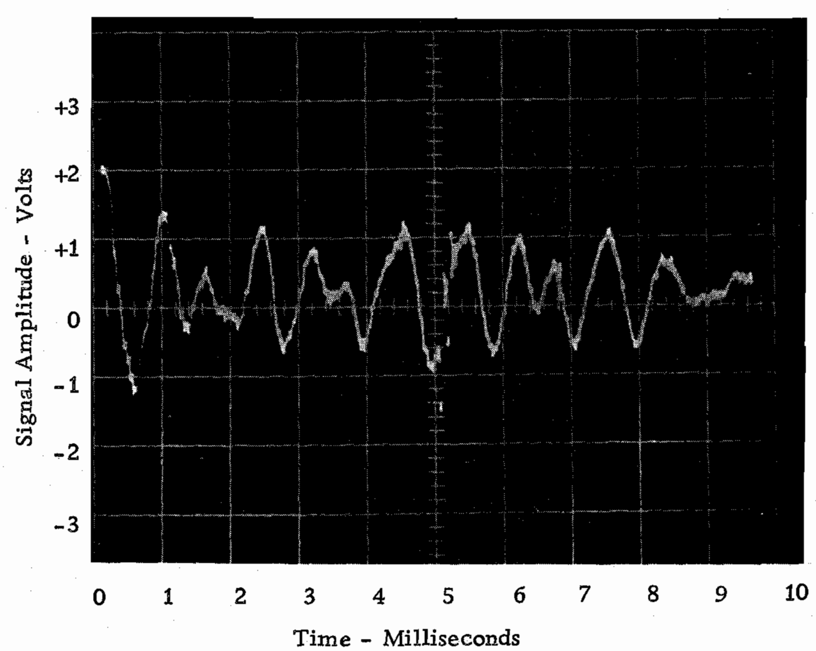


Figure 2b. (continued)

selected as the signal of interest, and the values of the sampled signal within this area were left in the computer's memory bank.

The digitized crab signal was then given a code recognition number and stored on magnetic tape for transportation to the Computer Center. Here the calculation of the autocorrelation function and the power density spectrum was performed on a computer with a larger storage capacity.

Computer Calculations

There are two procedures by which the power spectrum of a time varying signal may be obtained. These procedures are outlined below.

$$(1) \quad f(t) \xrightarrow{\text{computation}} R(\tau) \xrightarrow{\text{transformation}} |F(\omega)|^2$$

$$(2) \quad f(t) \xrightarrow{\text{transformation}} F(\omega) \xrightarrow{\text{multiplication}} |F(\omega)|^2$$

where $f(t)$ = a time varying signal

$R(\tau)$ = the autocorrelation of $f(t)$

$F(\omega)$ = the Fourier transform of $f(t)$

The first method was selected for two reasons; one, the analysis of the autocorrelation function of a crab signal was desired, and two, the transform equation to provide $|F(\omega)|^2$ from $R(\tau)$ would be simplified since $R(\tau)$ is an even function.

Before calculating these quantities any D. C. component contained in the time varying signal $f(t)$ was removed by subtracting f (t)av. from each sample point in the time series. The autocorrelation function is defined by

$$R(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} f(t)\, f(t+\tau)\, dt \tag{1}$$

where $f(t)$ = the time varying signal

T = the period of the signal

The autocorrelation function, $R(\tau)$, of the time varying signal, $f(t)$, was determined from equation 1. The power density spectrum was then calculated. This was done by multiplying $R(\tau)$ by a window function, $g(\tau)$, and transforming the product into the frequency domain domain using the Fourier transform equation.

$$X(f) = \int_{-\infty}^{\infty} x(t)\, e^{-j\omega t}\, dt \tag{2}$$

The function $g(\tau)$ is defined by the following equation.

$$\begin{aligned} g(\tau) &= 1 - 6u^2 + 6|u|^3 && |u| < 1/2 \\ &= 2(1-|u|)^3 && 1/2 \leqslant u \leqslant 1 \\ &= 0 && |u| > 1 \end{aligned} \tag{3}$$

where $u = \dfrac{|\tau|}{T_m}$ (4)

T_m = the maximum time of the signal

This function is called a Parzen window (Parzen, 1961). The window acts as a smoothing function, smoothing the resulting estimated power density spectrum. The window also affects the bias and the variance of the estimated spectrum to minimize the mean square error of the estimate. This type of window was selected because the side lobes of the frequency spectrum of this function are very small. Since the multiplication of $g(\tau)$ and $R(\tau)$ in the time domain corresponds to convolving $g(\omega)$ and $R(\omega)$ in the frequency domain, this characteristic of $g(\omega)$ is a desirable one. Several window widths were examined and a width of 1/10 the crab signal's length gave the best results.

IV. RESULTS

The Dungeness crab (*Cancer magister*) and the Japanese red rock crab (*Cancer productus*) signals selected for investigation were analyzed to determine the duration time, the frequency content, the auto-correlation function, and the power density spectrum of each individual signal.

Duration Time

It was stated earlier that the basic sound produced by crustaceans lasted about one millisecond and contained frequencies throughout the entire audible spectrum (Tavolga, 1967). The data obtained in this investigation did not fully agree with this statement. A total of eighty-three signals were analyzed from isolated, identified crabs. All of these signals lasted longer than the predicted one millisecond, with duration times ranging from 2.8 milliseconds to 30.0 milliseconds. These are the minimum and the maximum signal lengths recorded from identified crabs. The minimum signal length was produced by a Dungeness female crab, and the maximum signal length was produced by a Japanese red rock female crab. The maximum signal length recorded from a Dungeness male crab was 26.5 milliseconds.

The signals were separated into five groupings according to time duration; (1) those less than five milliseconds, (2) five to ten milliseconds, (3) ten to 15 milliseconds, (4) 15 to 20 milliseconds, and (5) greater than 20 milliseconds. The results obtained for all crabs are tabulated in Table III, and shown in graphical form in Figure 3.

The Dungeness male crabs were divided into two groups; large males measuring five or more inches across the carapace, and small males measuring less than five inches. The percentage of large male Dungeness crab signals in the range of five to ten milliseconds was 56.5%. The percentage of signals for the small Dungeness males in the same range was 69.2%, and for Dungeness females the figure was 52.4%. As can be seen from the table the largest percentage of all signals analyzed lies between five and ten milliseconds duration time.

Frequency Content

The frequency range of the analyzed signals agrees with the range stated for all crustaceans by Tavolga (1967). The signals produced by both species contained frequency components throughout the range of 800-15000 hertz, the pass-band of the input filter employed during recording. Signals were obtained with frequency ranges which did not extend throughout the entire range, but the majority of the signals possessed frequencies through most of this range.

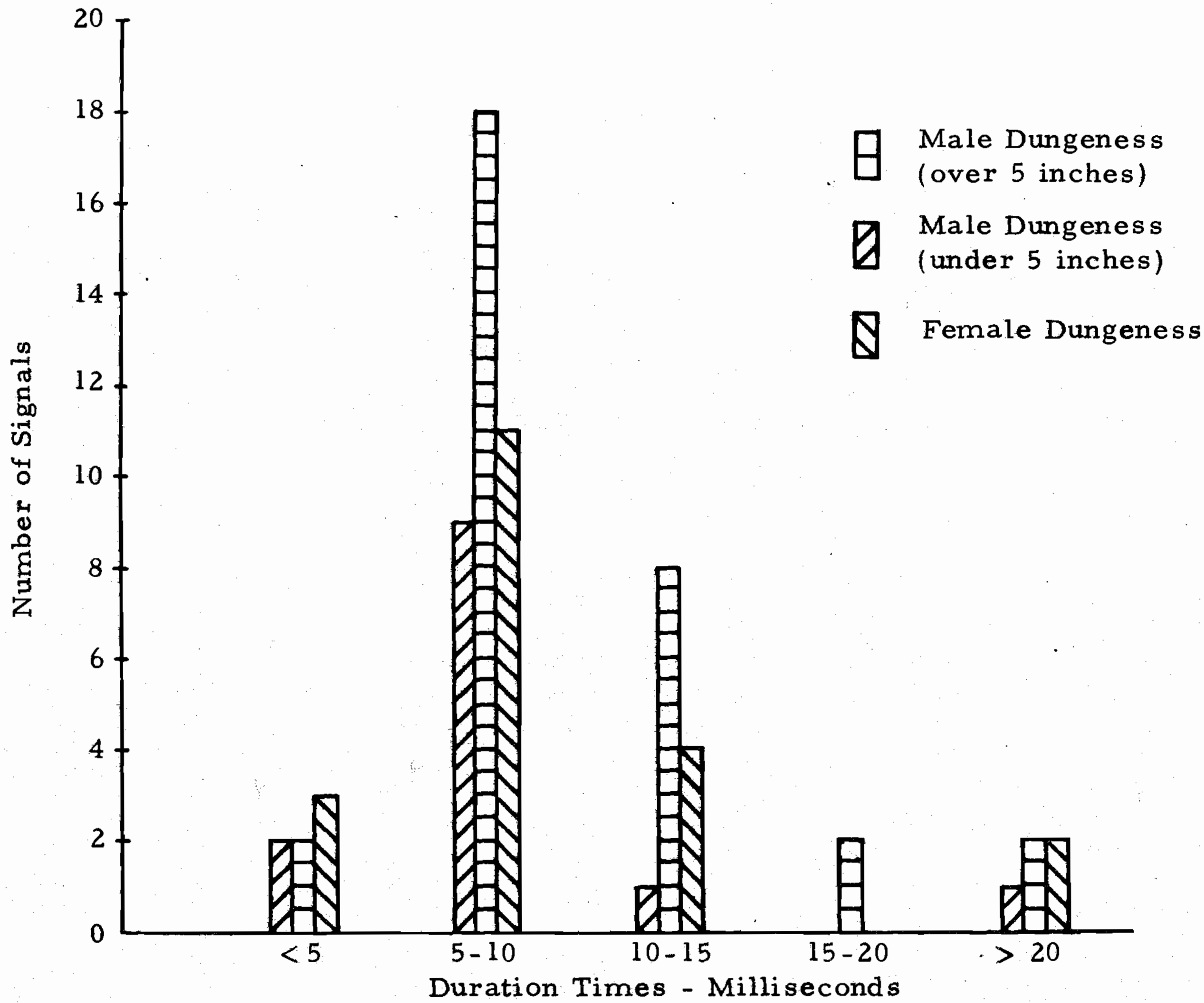


Figure 3. Distribution of signal duration times for Dungeness crab signals.

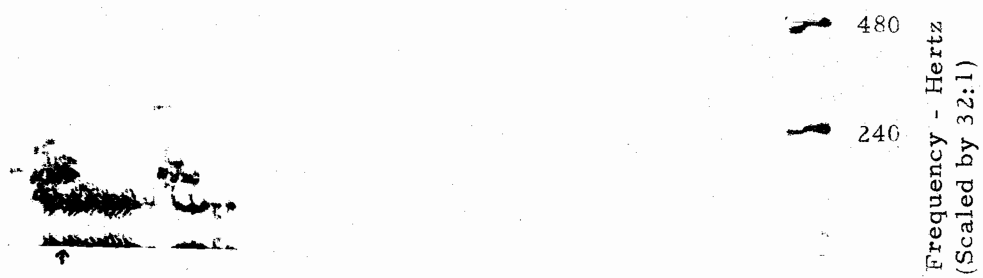


Figure 4. Frequency content of a signal obtained from a 6 inch male Dungeness crab.

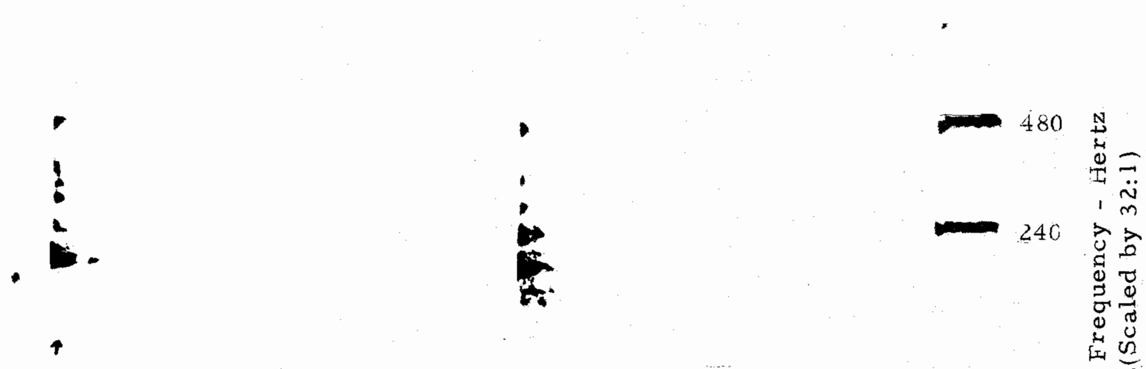


Figure 5. Frequency content of a signal obtained from a $5\frac{1}{2}$ inch male Dungeness crab.

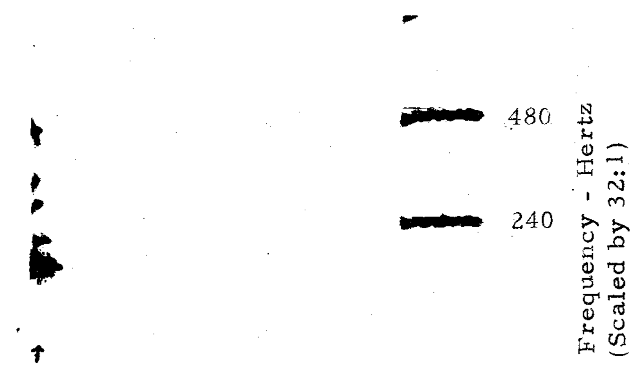


Figure 6. Frequency content of a signal obtained from a 6 inch male Dungeness crab.

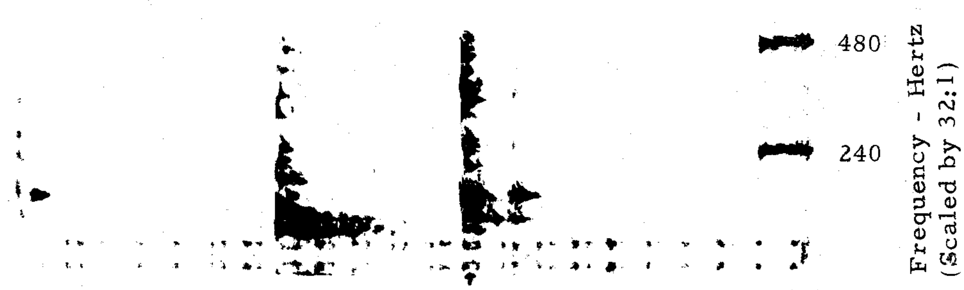


Figure 7. Frequency content of a signal obtained from a 4 inch male Dungeness crab.

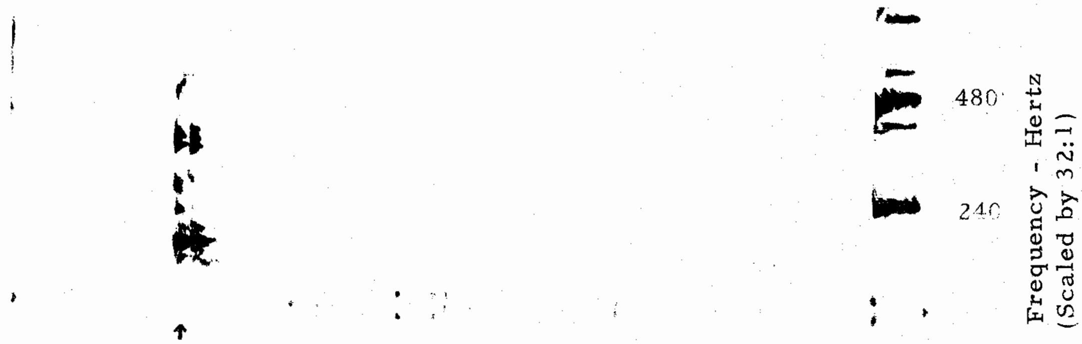


Figure 8. Frequency content of a signal obtained from a 4 inch male Dungeness crab.

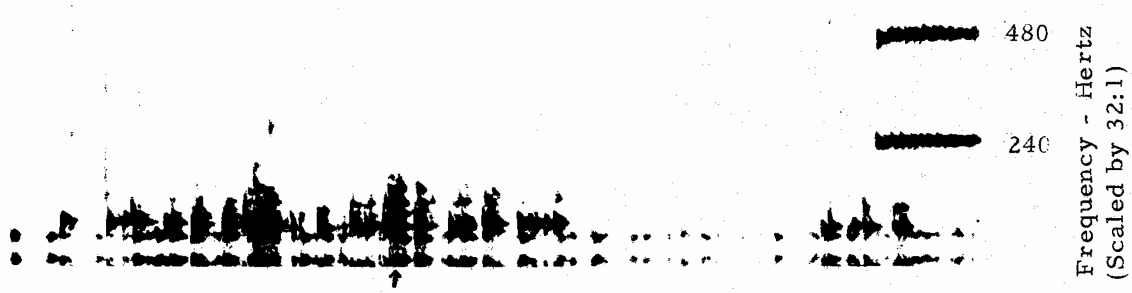


Figure 9. Frequency content of a signal obtained from a 4 inch female Dungeness crab.

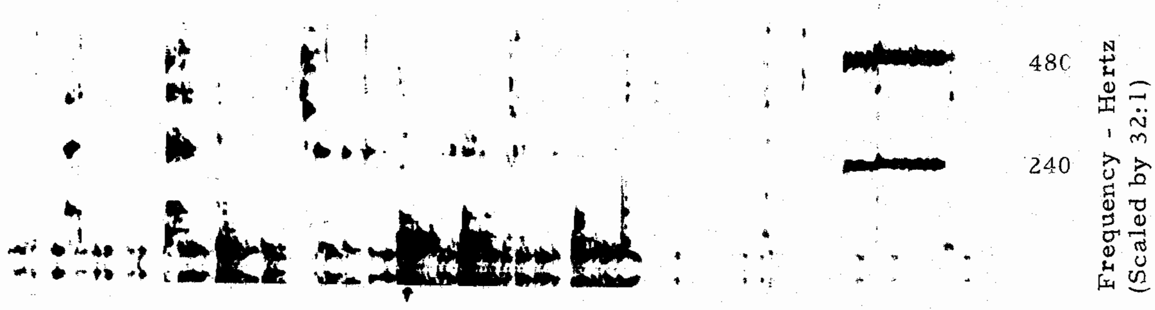


Figure 10. Frequency content of a signal obtained from a 4 inch female Dungeness crab.

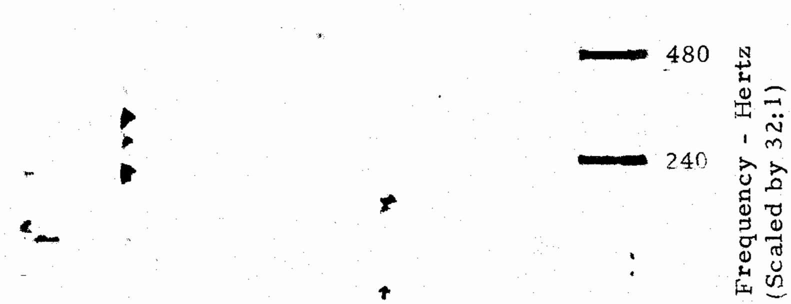


Figure 11. Frequency content of a signal obtained from a $3\frac{1}{2}$ inch female Dungeness crab.

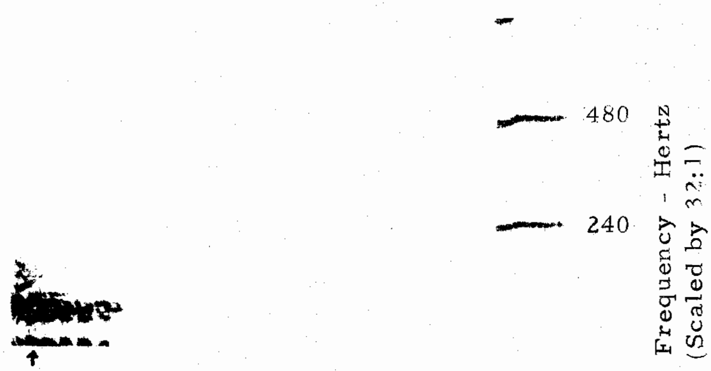


Figure 12. Frequency content of a signal obtained from an unidentified crab in the open bay.

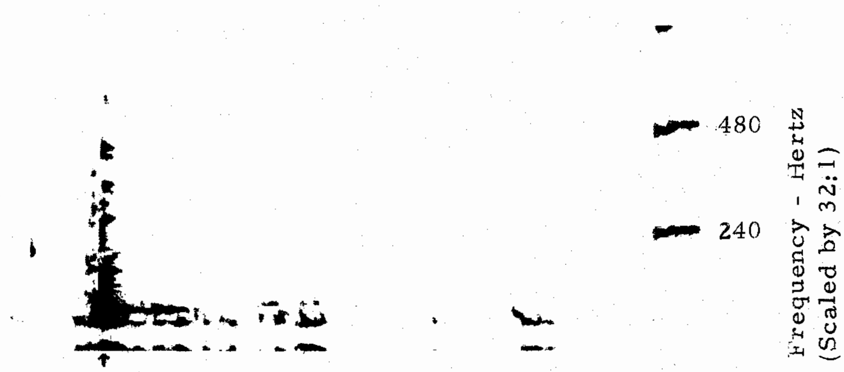


Figure 13. Frequency content of a signal obtained from an unidentified crab in the open bay.

Examination of the sonograms shows that, while the total frequency range of a signal is generally broad, most of the power contained in the signal is concentrated in a relatively narrow band of frequencies. In addition to having a narrow band characteristic, most of the signals possessed a unique total frequency characteristic. Many of the signals had a similar frequency content, but none were found with identical characteristics. The frequency content, time duration, the frequency range between the 1/2 power points, and the maximum power of each signal are tabulated in Table VI. The power values in this table are normalized to a one ohm output resistance of the transducer.

Autocorrelation Function

The autocorrelation functions obtained from computer analysis tend to form three different types of curves. These three types are: (1) scattered points with no discernible wave pattern, (2) a decaying sinusoidal wave shape (example; Figure 20), and (3) a sinusoidal wave shape displaying nodal and anti-nodal behavior (example; Figure 14). Most of the autocorrelation curves obtained are of the sinusoidal varieties. The percentage of curves which fall into these three groups are tabulated for each type of crab in Table IV. The number of signals produced by Dungeness crabs in these groups are shown in graphical form in Figure 24.

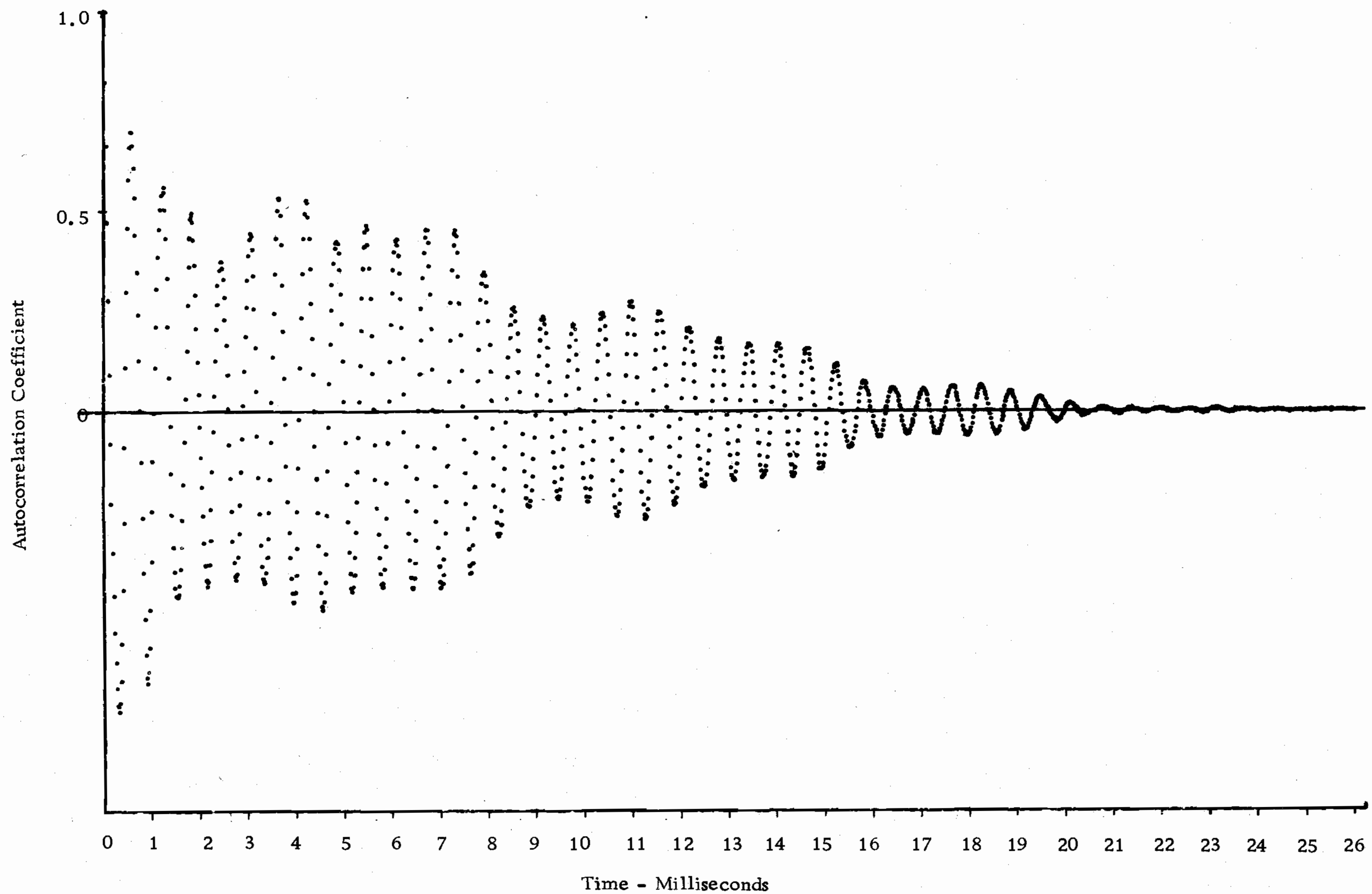


Figure 14. Autocorrelation function of a signal obtained from a 6 inch male Dungeness crab.

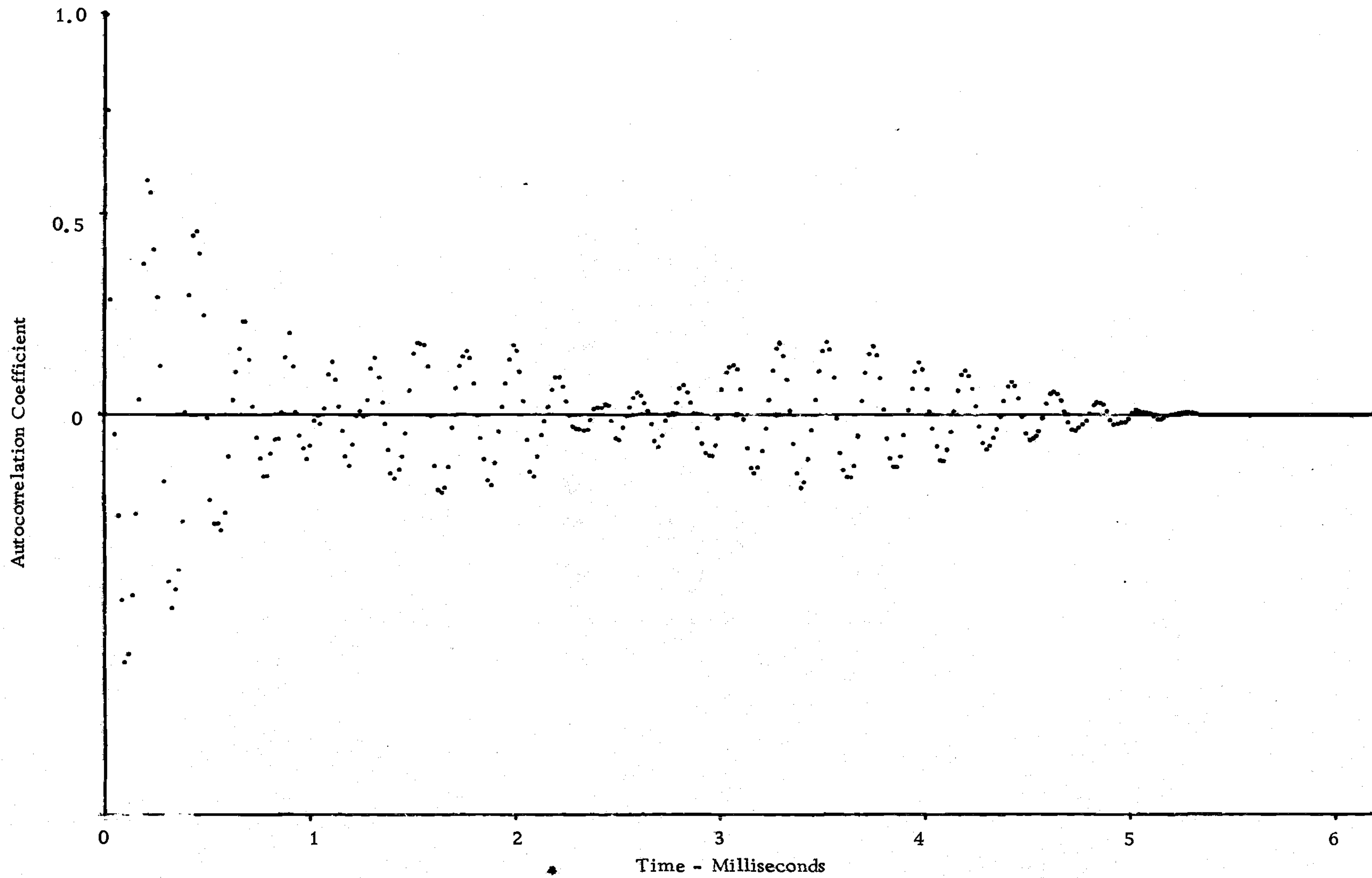


Figure 15. Autocorrelation function of a signal obtained from a 5 1/2 inch male Dungeness crab.

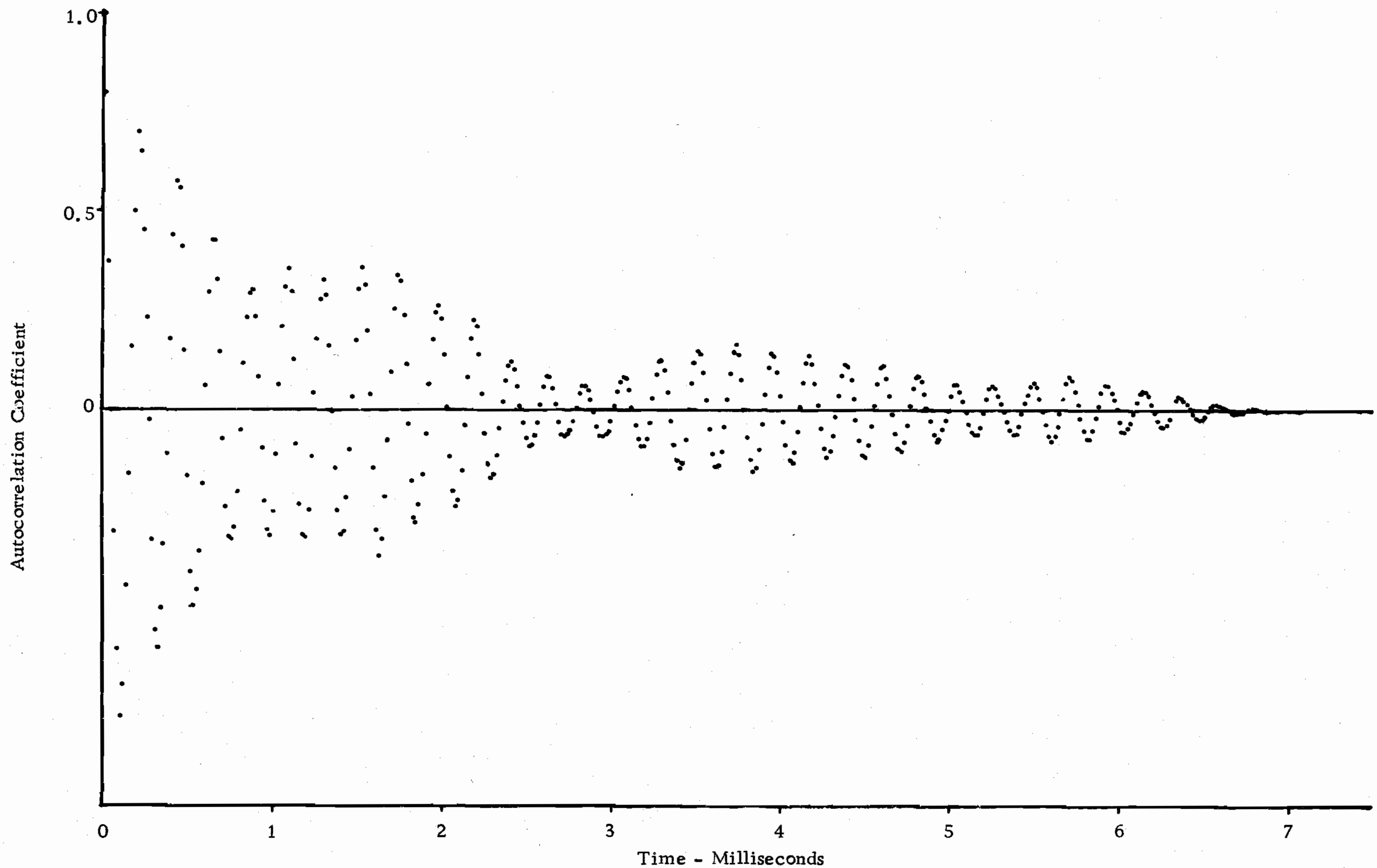


Figure 16. Autocorrelation function of a signal obtained from a 6 inch male Dungeness crab.

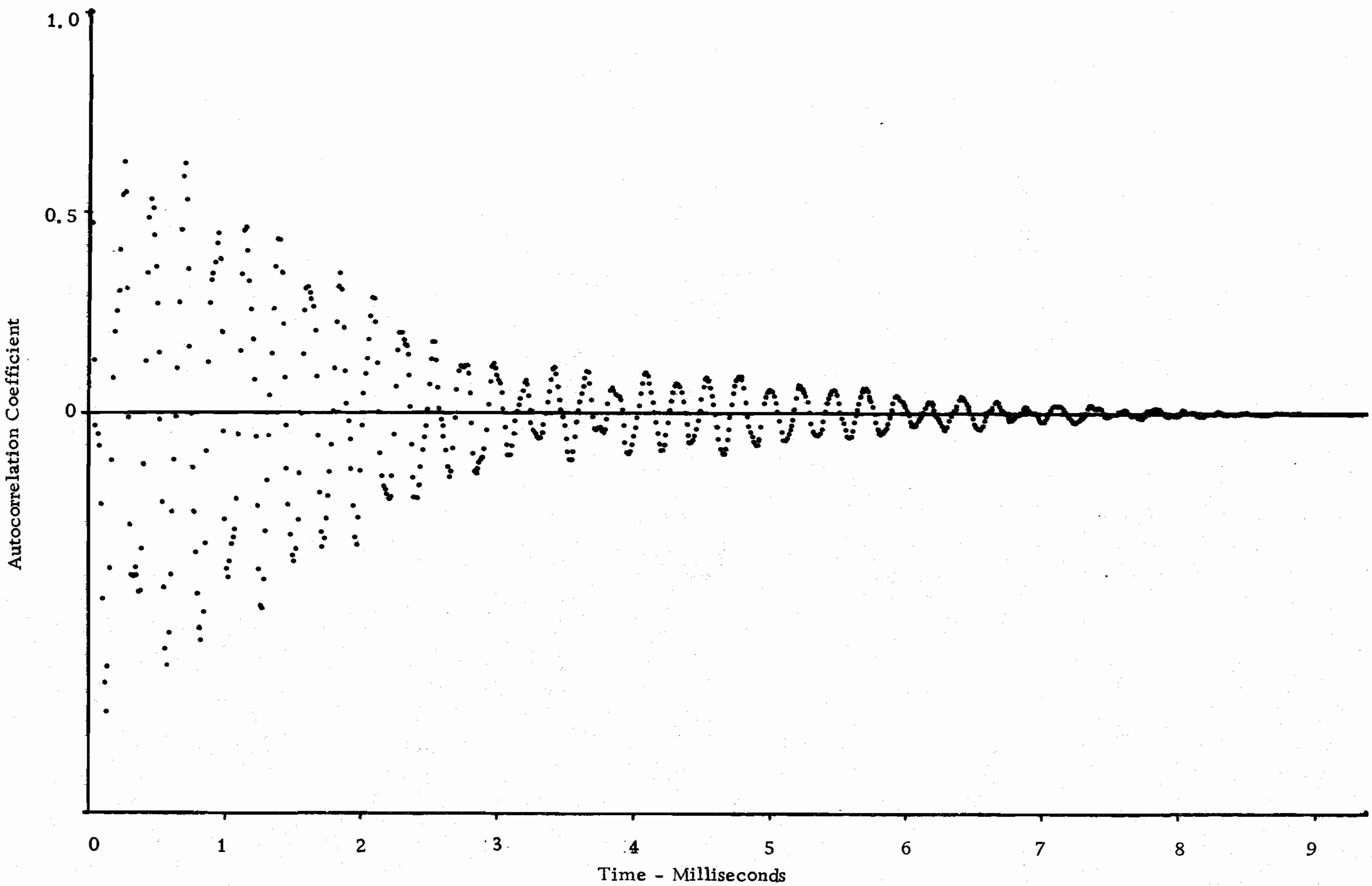


Figure 17. Autocorrelation function of a signal obtained from a 4 inch male Dungeness crab.

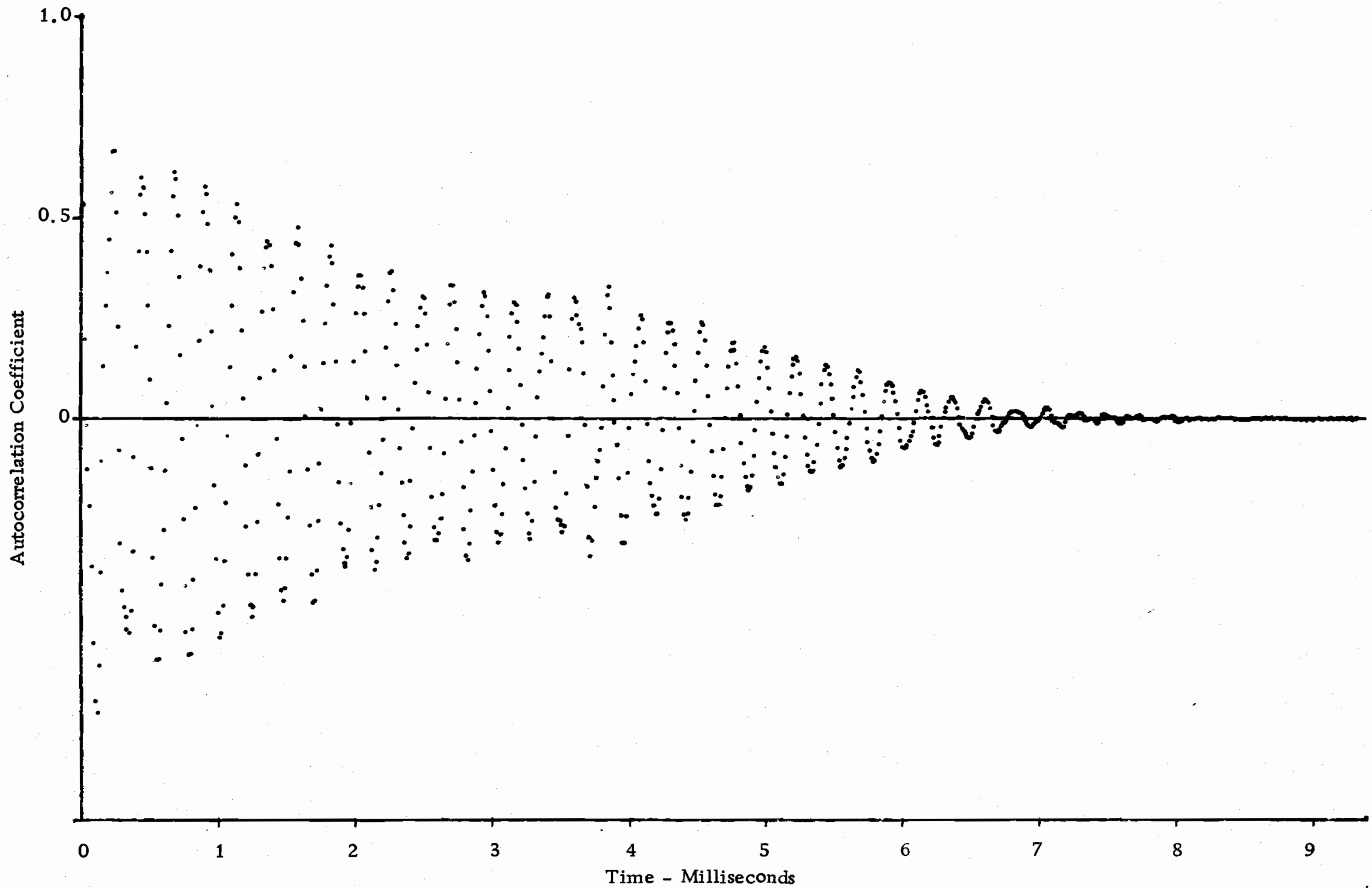


Figure 18. Autocorrelation function of a signal obtained from a 4 inch male Dungeness crab.

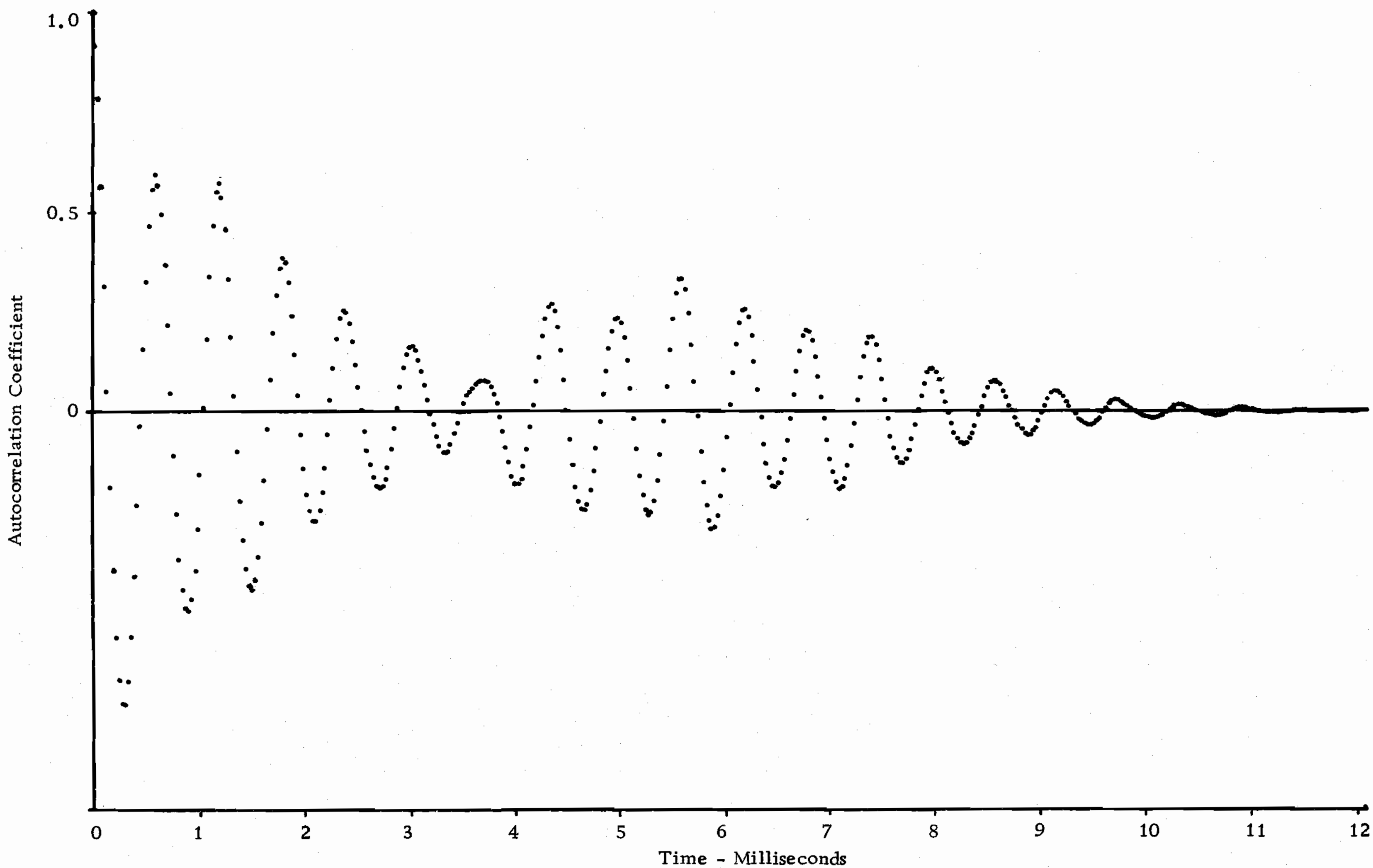


Figure 19. Autocorrelation function of a signal obtained from a 4 inch female Dungeness crab.

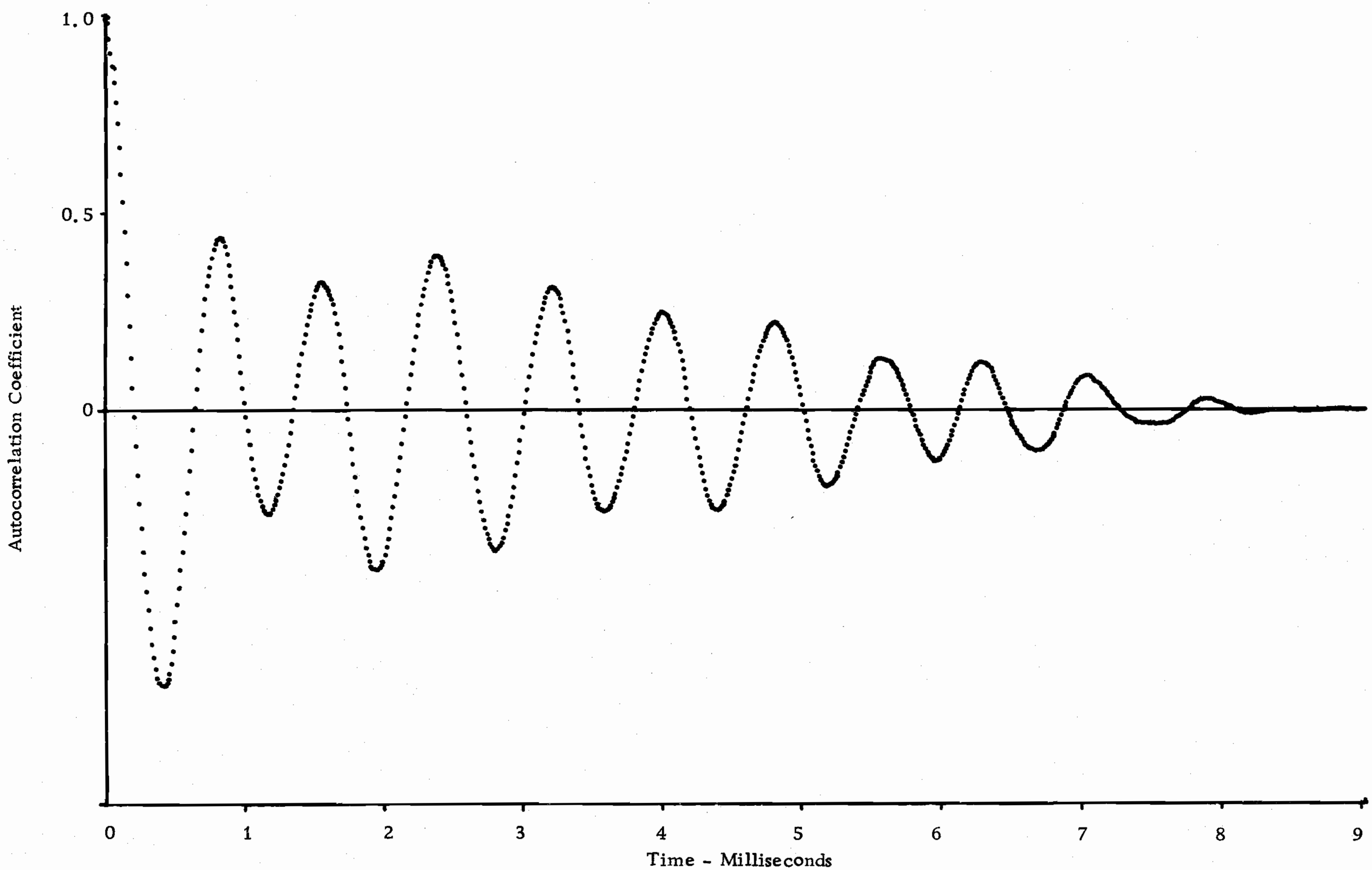


Figure 20. Autocorrelation function of a signal obtained from a 4 inch female Dungeness crab.

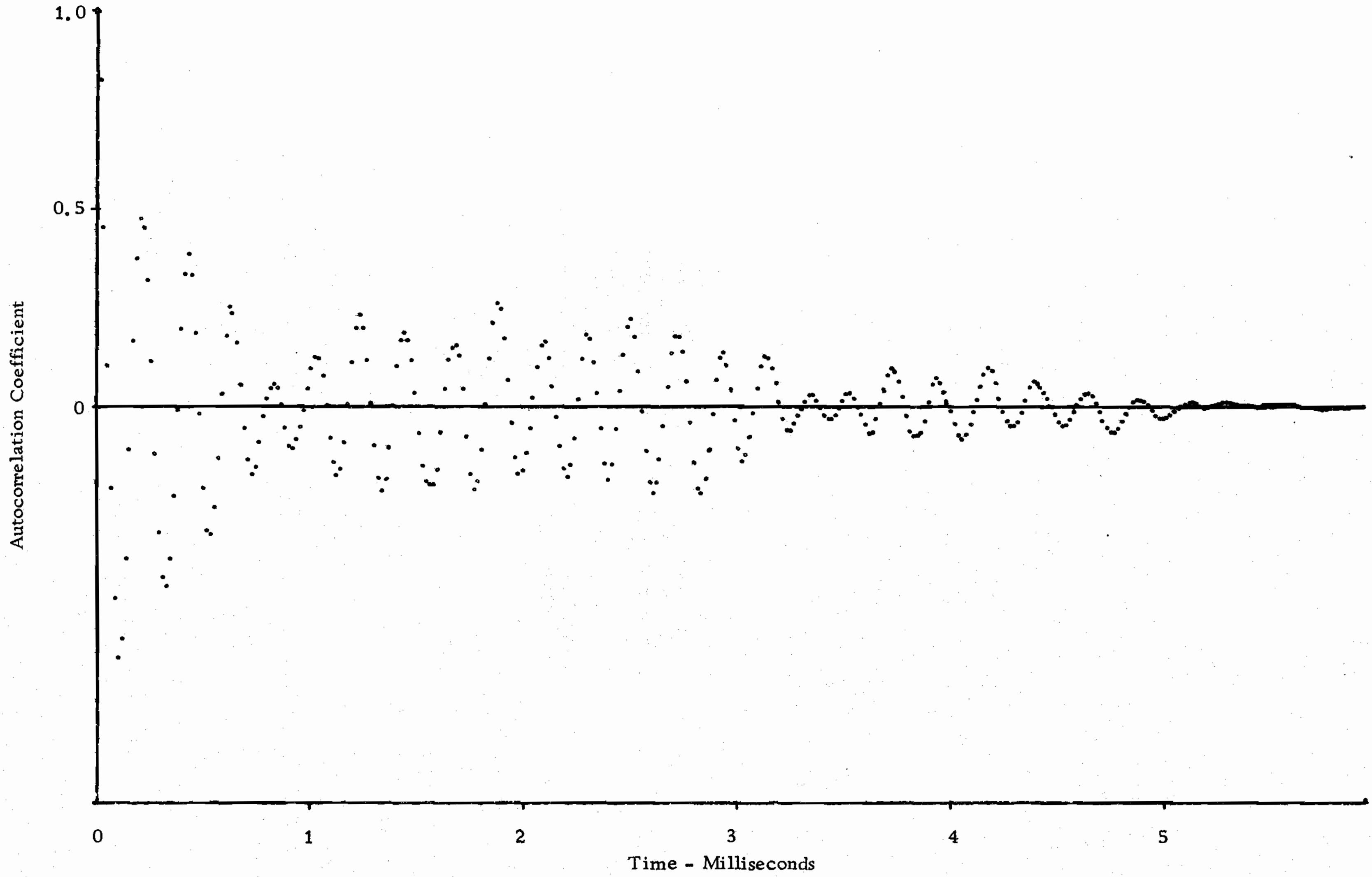


Figure 21. Autocorrelation function of a signal obtained from a 3 1/2 inch female Dungeness crab.

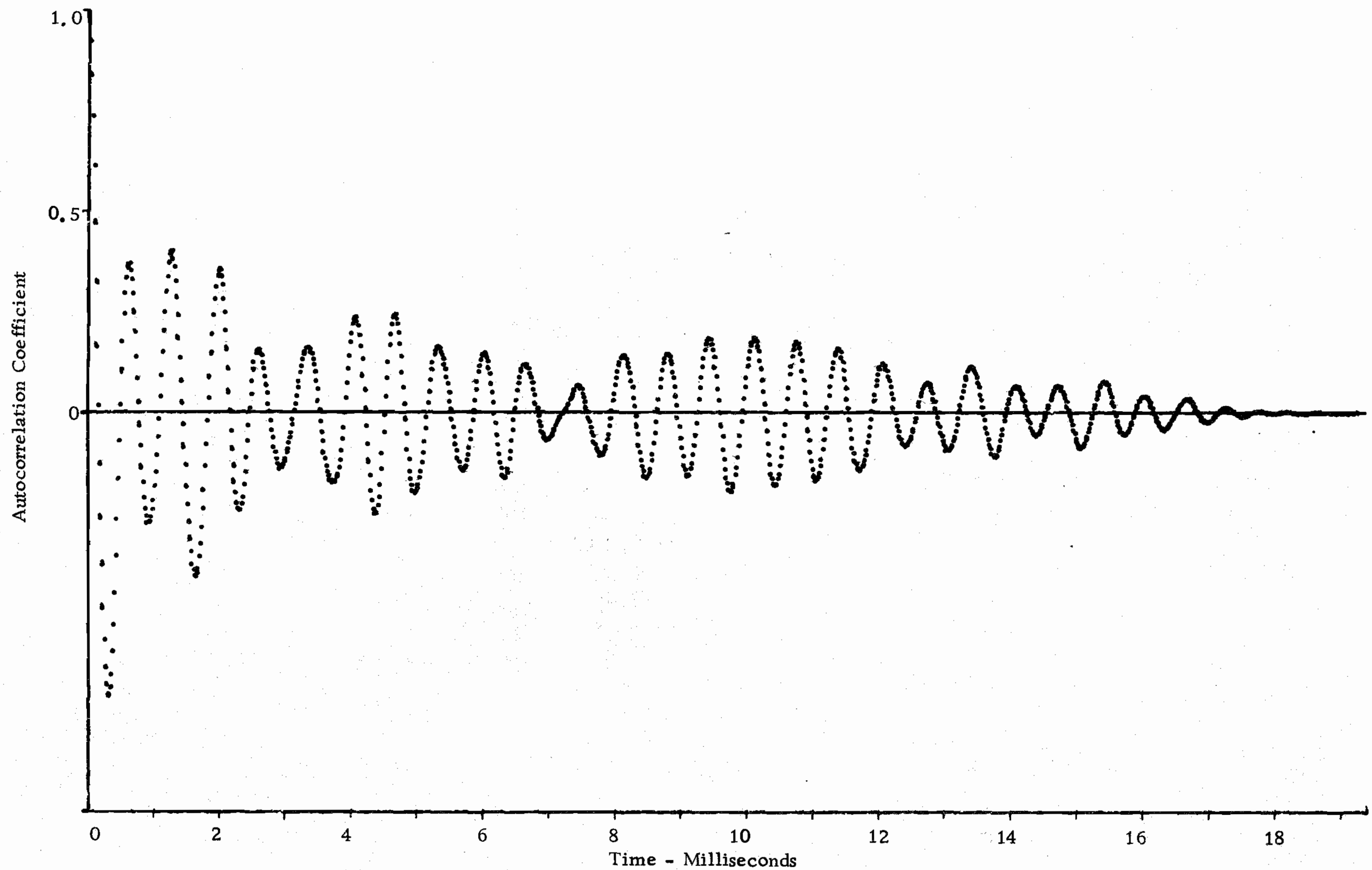


Figure 22. Autocorrelation function of a signal obtained from an unidentified crab in the open bay.

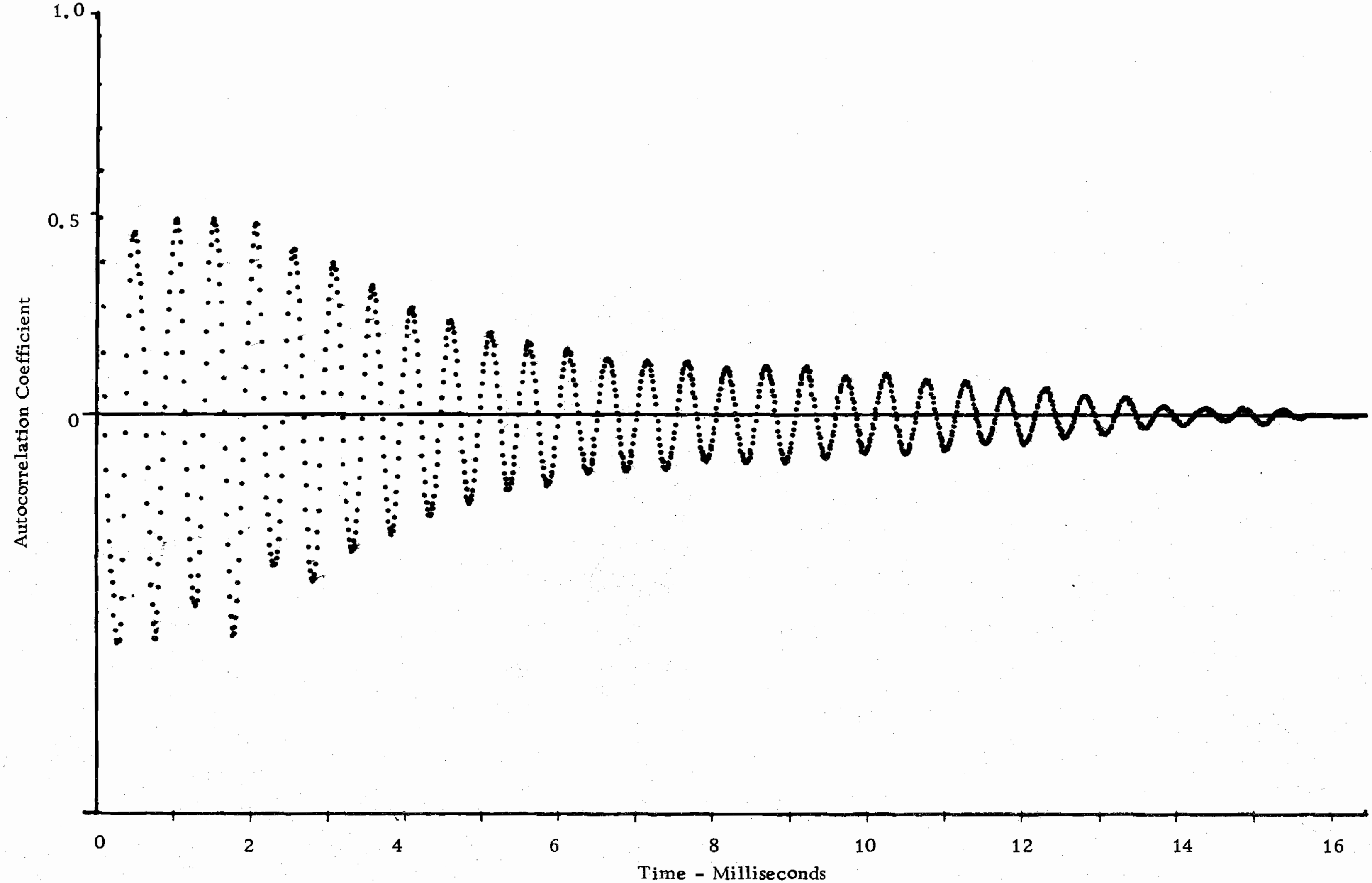


Figure 23. Autocorrelation function of a signal obtained from an unidentified crab in the open bay.

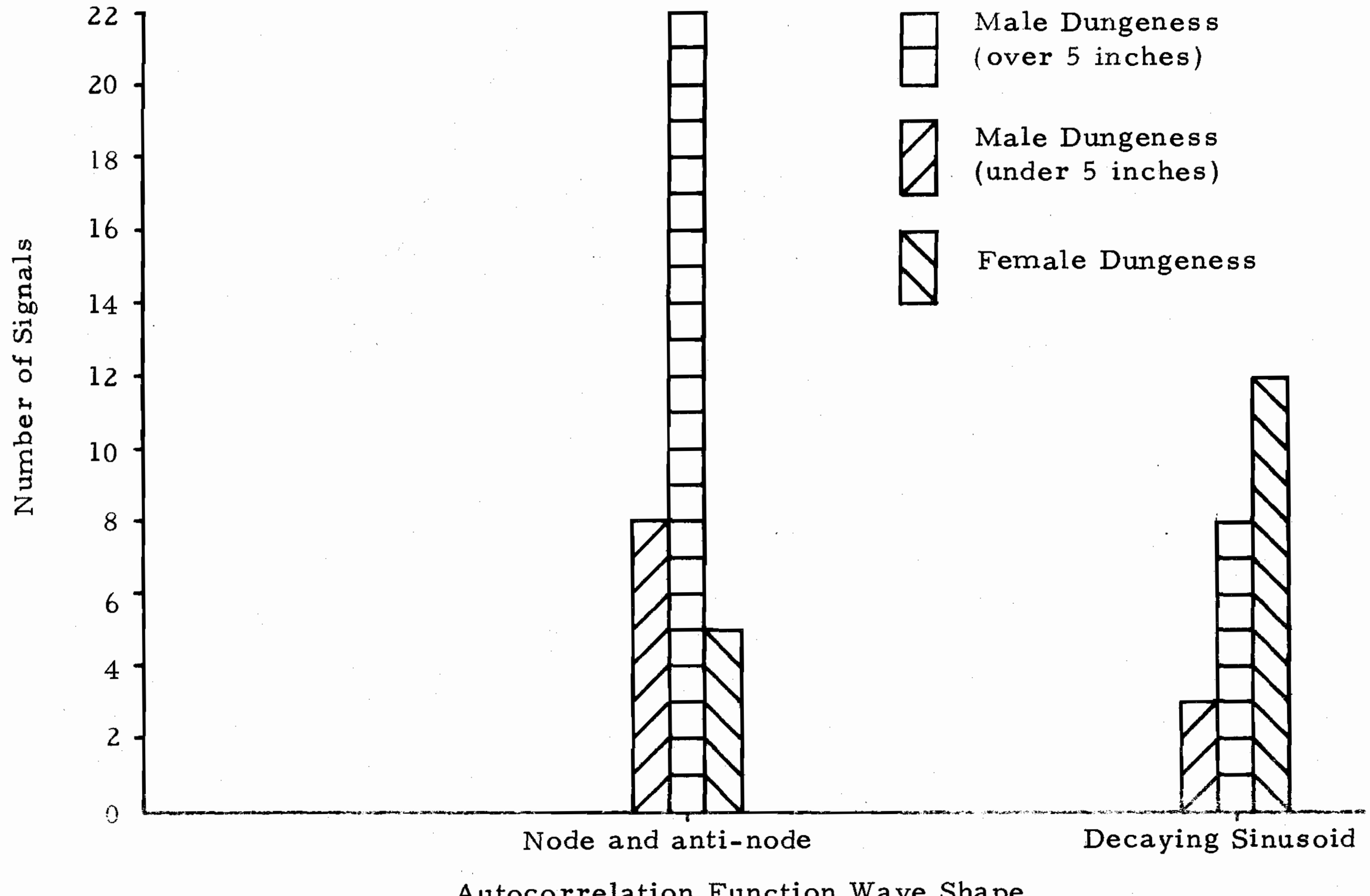


Figure 24. Distribution of autocorrelation function wave shapes in the Dungeness crab signals.

In the large male Dungeness crabs 66.6% of the autocorrelation curves display nodal and anti-nodal behavior. Of the remaining curves, 24.2% are of the decaying sinusoidal variety and 9.2% are patternless. The smaller Dungeness male crabs show a decaying sinusoidal wave shape in 23.1% of the curves. Nodal and anti-nodal behavior occurs in 69% of the curves, and 7.3% are patternless. The female Dungeness crabs showed nodal and anti-nodal behavior in 25% of the curves, a decaying sinusoid in 60%, and 15% contained no discernible pattern.

The small percentage of patternless curves obtained are, in part, due to recording bad data, errors in signal selections, and errors introduced in signal transfer. The transfer of digital data from magnetic tape to computer memory bank introduced some errors due to the equipment involved. In three cases this procedure introduced enough errors that the signals were rejected by the computer.

Much of the information in the autocorrelation functions is directly related to the information contained in the power density spectrums. The frequency of the sinusoidal variations in the autocorrelation functions is also the center frequency of the power peak in the density spectrum. The frequency of the autocorrelation function is therefore a measure of where the signal's power is concentrated.

A relationship should also exist in the time period between nodes and the frequency difference between power peaks. The nodal and anti-nodal behavior displayed by many of the signals is an indication that this relationship does exist. In the signals examined only two patterns of time intervals were apparent. The time period between nodes in the large male Dungeness autocorrelation functions was less than two milliseconds in 85% of the curves where a detectable time period existed. The time period between nodes in the Japanese red rock autocorrelation functions was four milliseconds in 67% of the curves. Time periods were present in small male and female Dungeness autocorrelation functions, but no pattern was apparent. A time period between nodes of two milliseconds corresponds to a frequency difference between power peaks of 500 hertz. The time period of four milliseconds corresponds to a frequency difference of 250 hertz. The band width used in estimating the power density spectrum was, in all cases, larger than 500 hertz, and therefore a second power peak less than 500 hertz from another power peak would not be detectable.

Power Density Spectrum

The power density spectrum of each signal was computed on a digital computer using a statistical estimation technique. Since

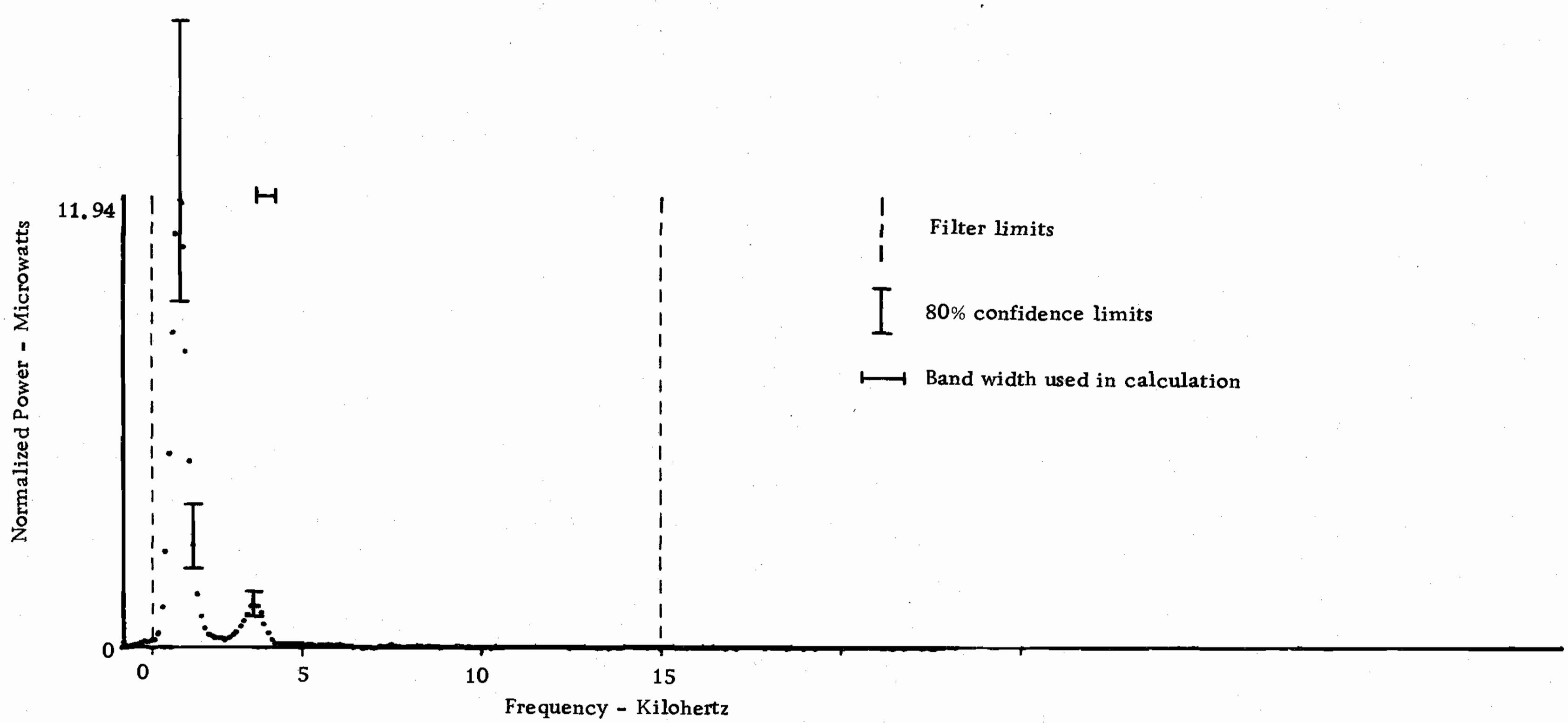


Figure 25. Power density spectrum of a signal obtained from a 6 inch male Dungeness crab.

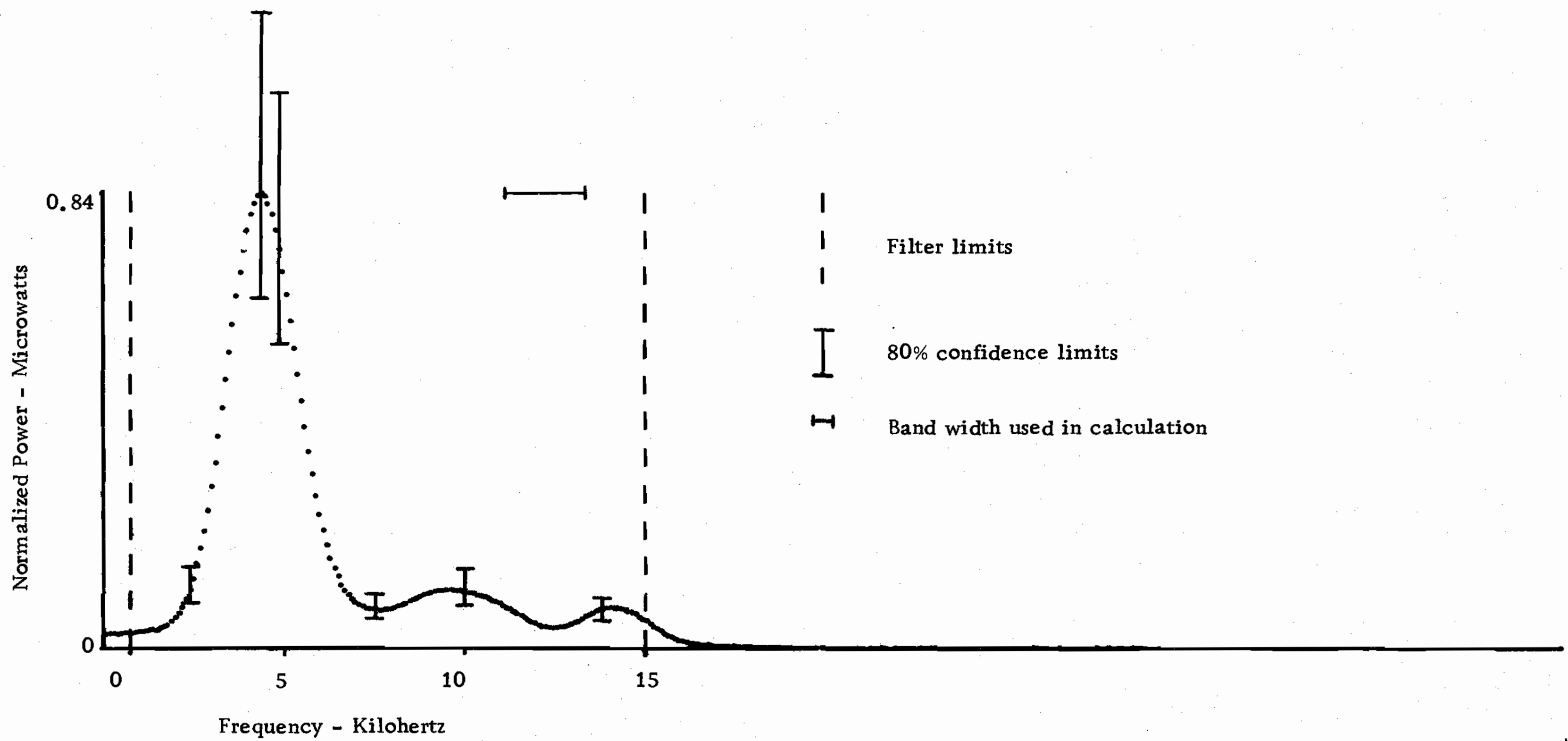


Figure 26. Power density spectrum of a signal obtained from a 5 1/2 inch male Dungeness crab.

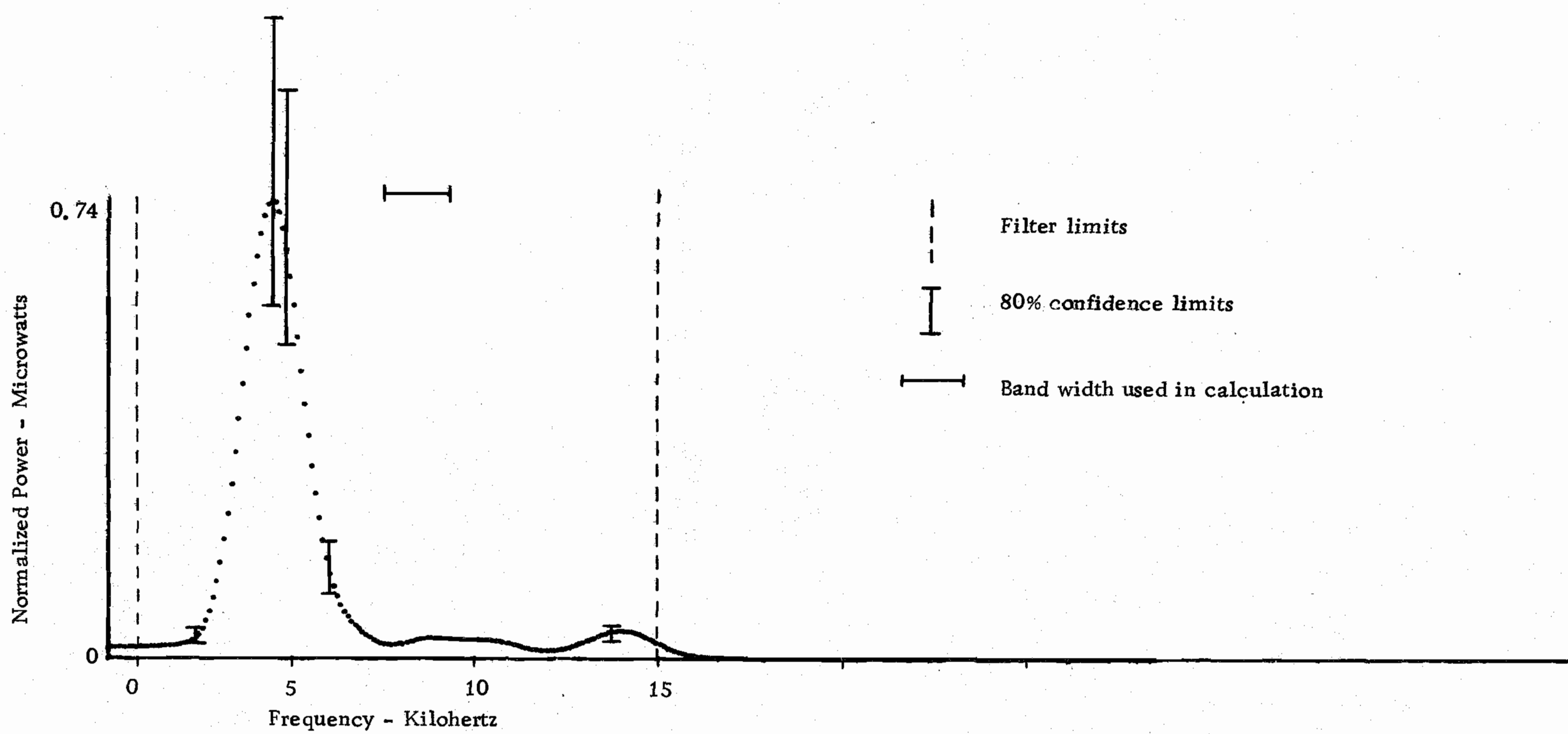


Figure 27. Power density spectrum of a signal obtained from a 6 inch male Dungeness crab.

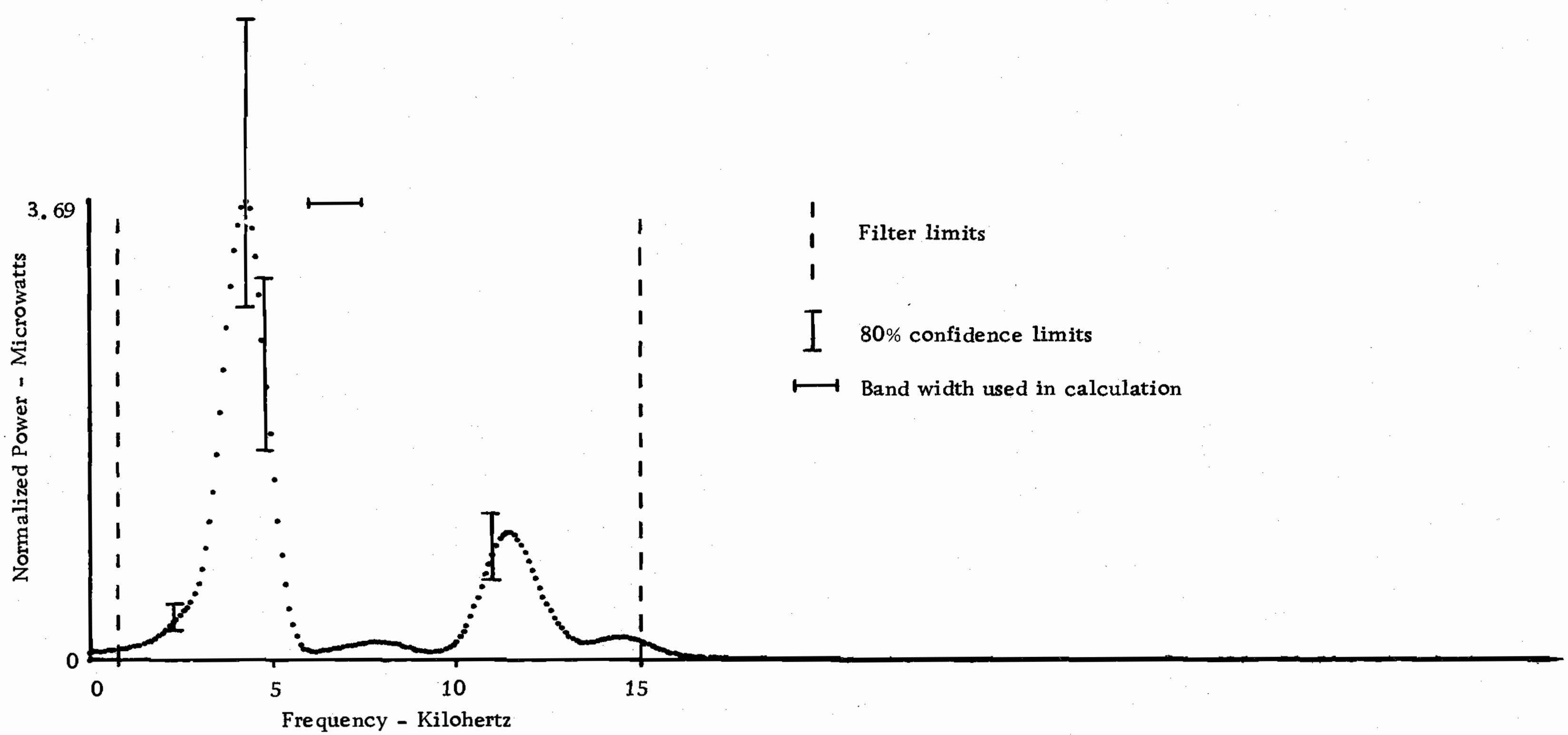


Figure 28. Power density spectrum of a signal obtained from a 4 inch male Dungeness crab.

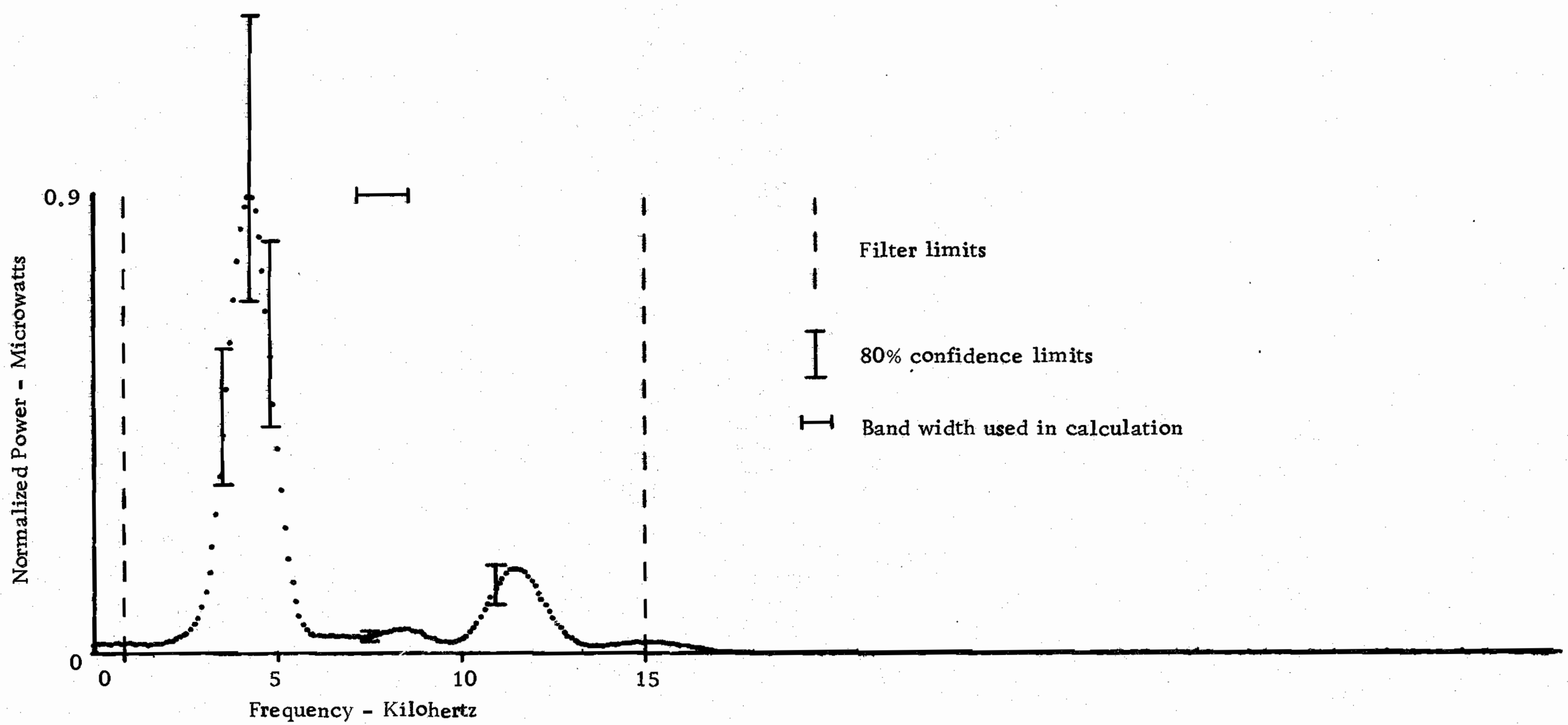


Figure 29. Power density spectrum of a signal obtained from a 4 inch male Dungeness crab.

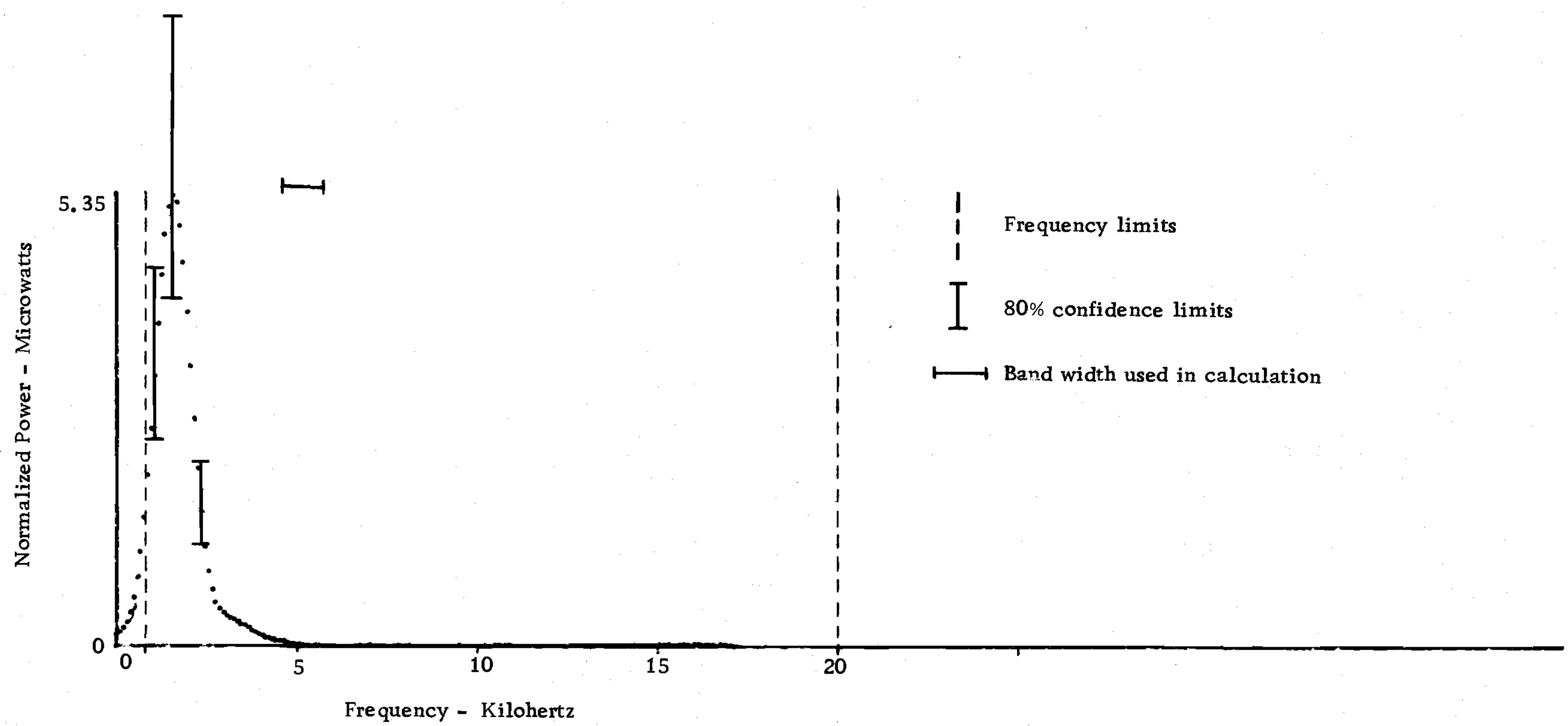


Figure 30. Power density spectrum of a signal obtained from a 4 inch female Dungeness crab.

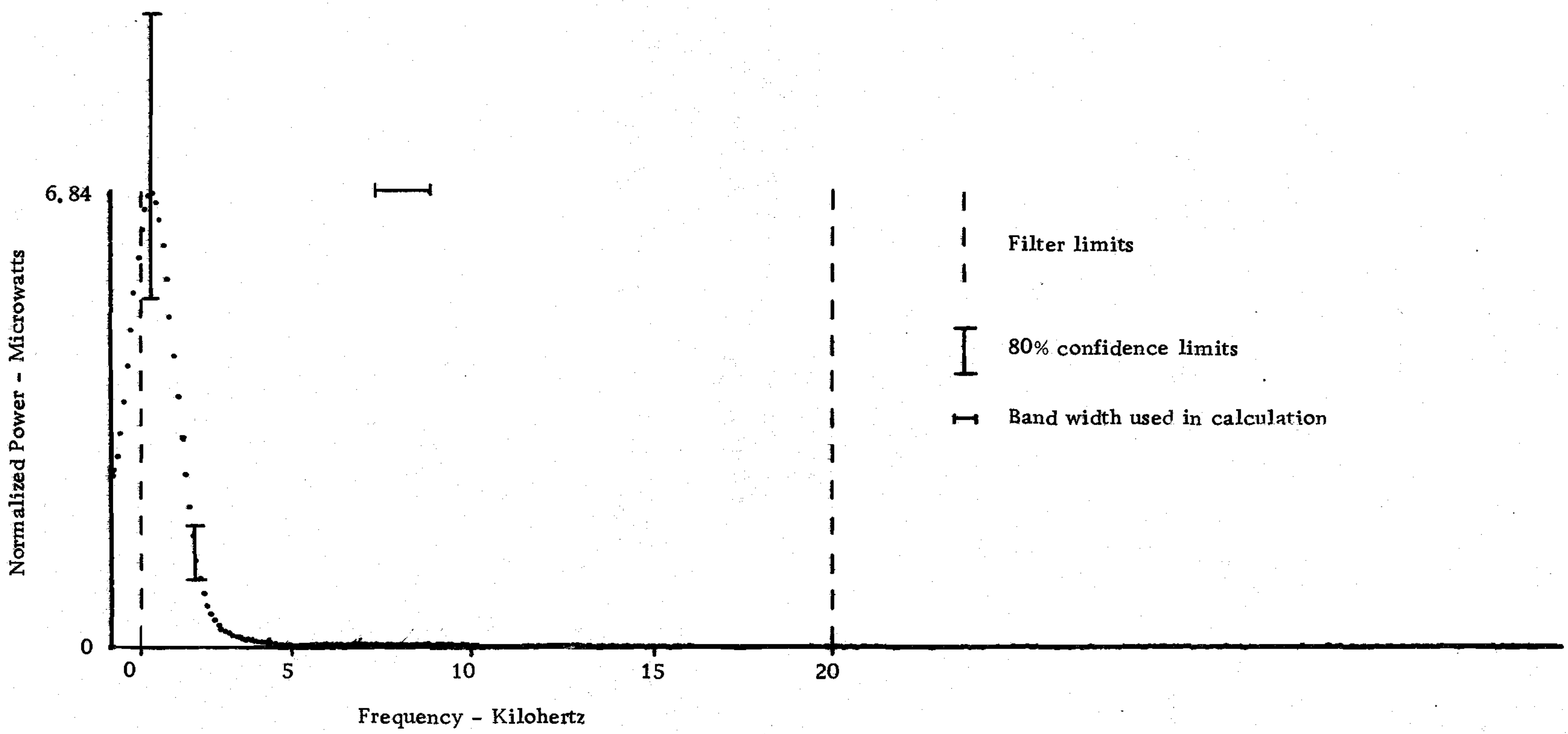


Figure 31. Power density spectrum of a signal obtained from a 4 inch female Dungeness crab.

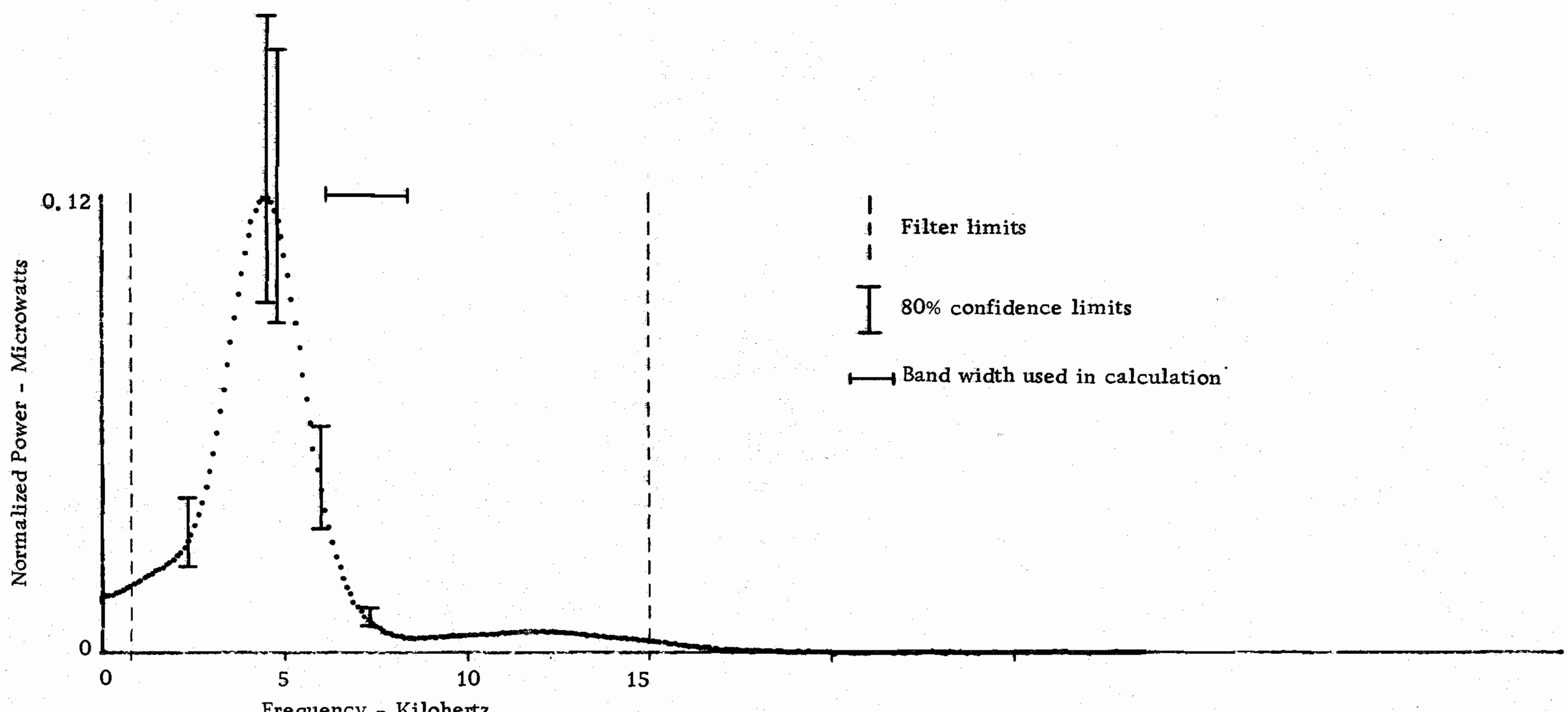


Figure 32. Power density spectrum of a signal obtained from a 3 1/2 inch female Dungeness crab.

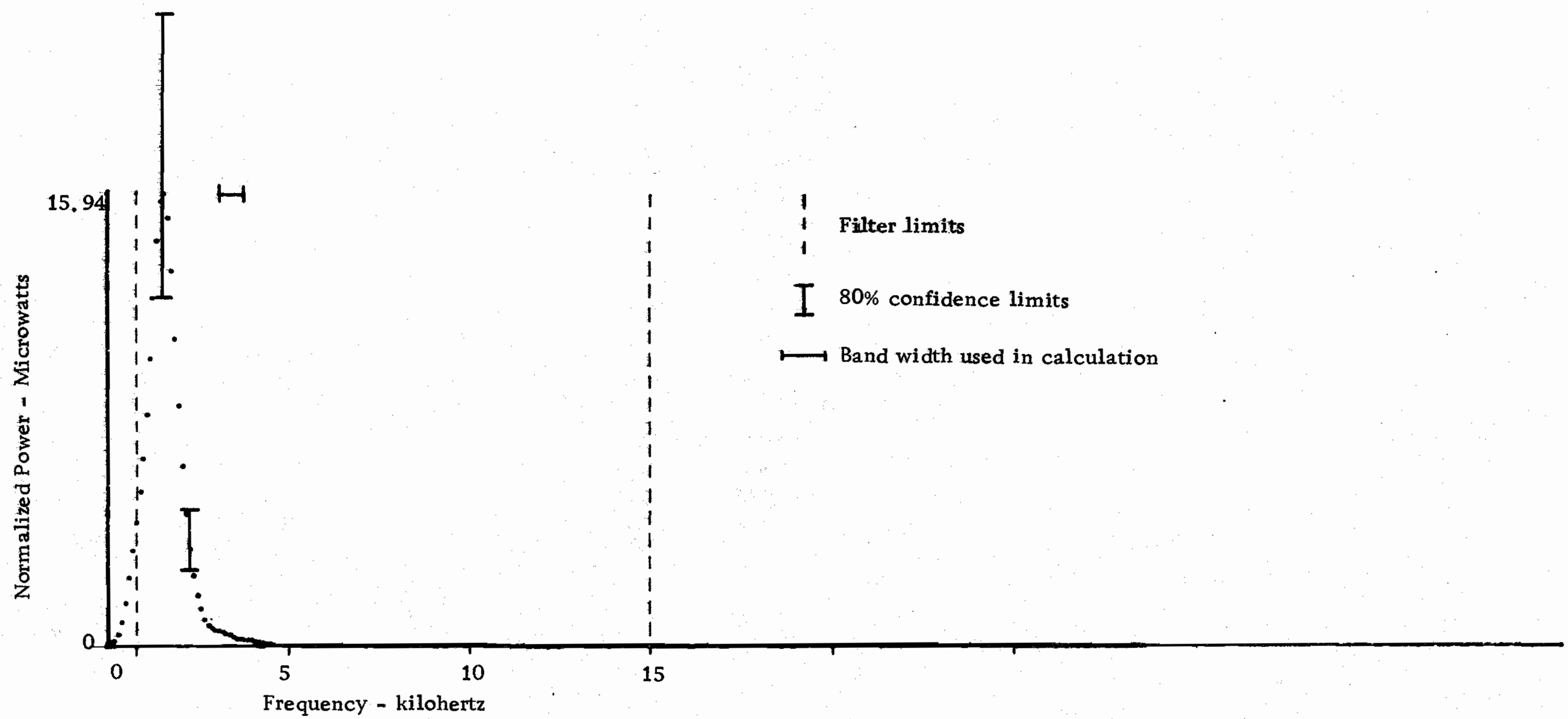


Figure 33. Power density spectrum of a signal obtained from an unidentified crab in the open bay.

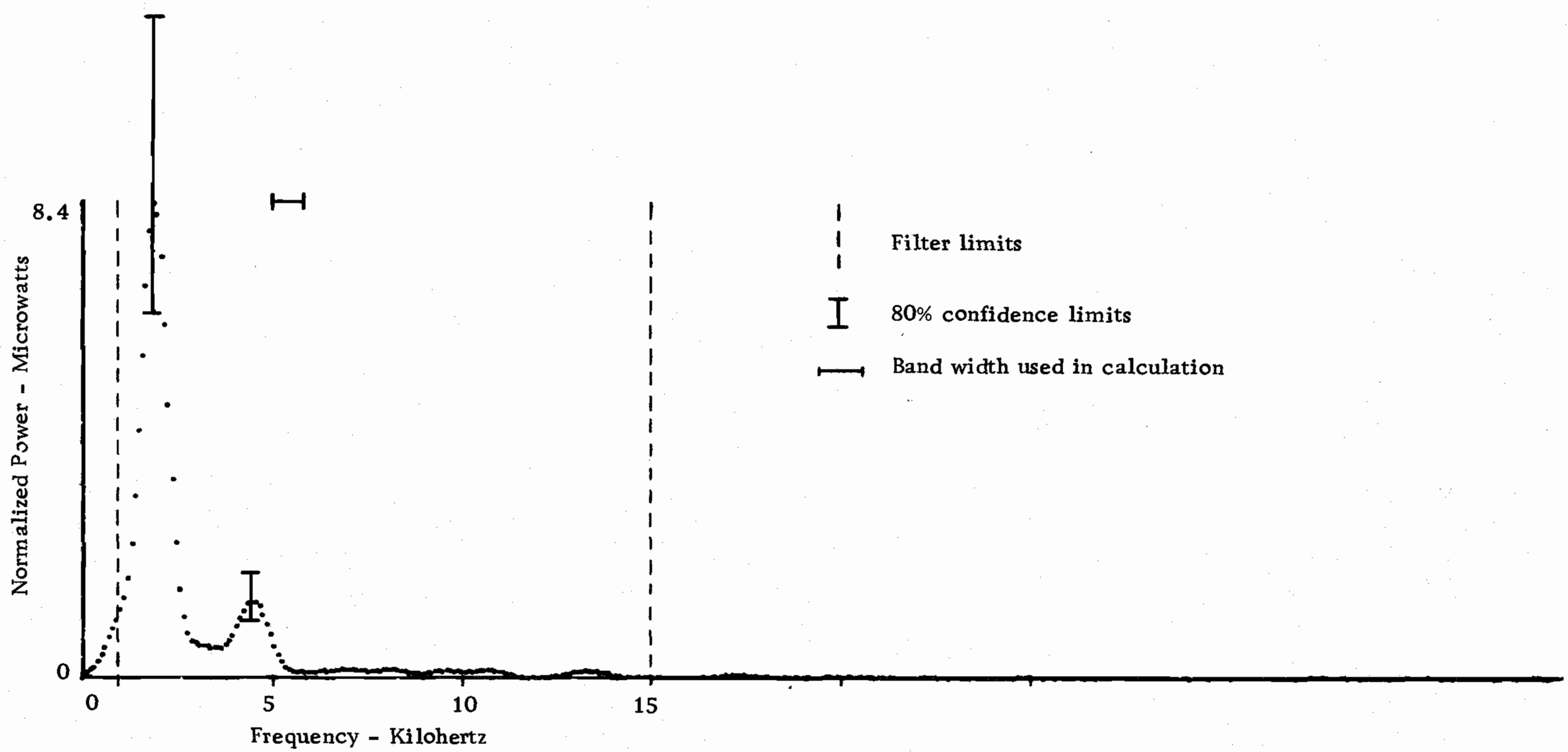


Figure 34. Power density spectrum of a signal obtained from an unidentified crab in the open bay.

an estimation was involved, the frequency at which maximum power occurred was determined from the sonogram and the power spectrum to provide a comparison between the two methods. The determination of the entire power spectrum and the maximum value of power could not be obtained from the sonogram since the particular machine used proved to be inadequate for this type of analysis.

The estimated power spectrums of the crab signals can be separated into three basic types: (1) the power is concentrated in one band of frequencies, (2) the power is concentrated in two separate bands of frequencies, and (3) the power is concentrated in more than two bands of frequencies. The percentage of signals for the different crabs in each of these categories are tabulated in Table V.

The larger percentage of all signals have one band of frequencies containing most of the power. Many of the power spectrums in this category have secondary power peaks, but the additional peaks possess only a very small portion of the total power.

The frequency which contained maximum power was determined from the power density specimens for the Dungeness crab signals. These frequencies were separated into six frequency ranges. The number of signals for large males, small males, and females which have a maximum power frequency in these ranges are shown in graphical form in Figure 35. Peak power frequencies in the range of 4000-6000 hertz occur in 69% of the large male crab signals. Small male

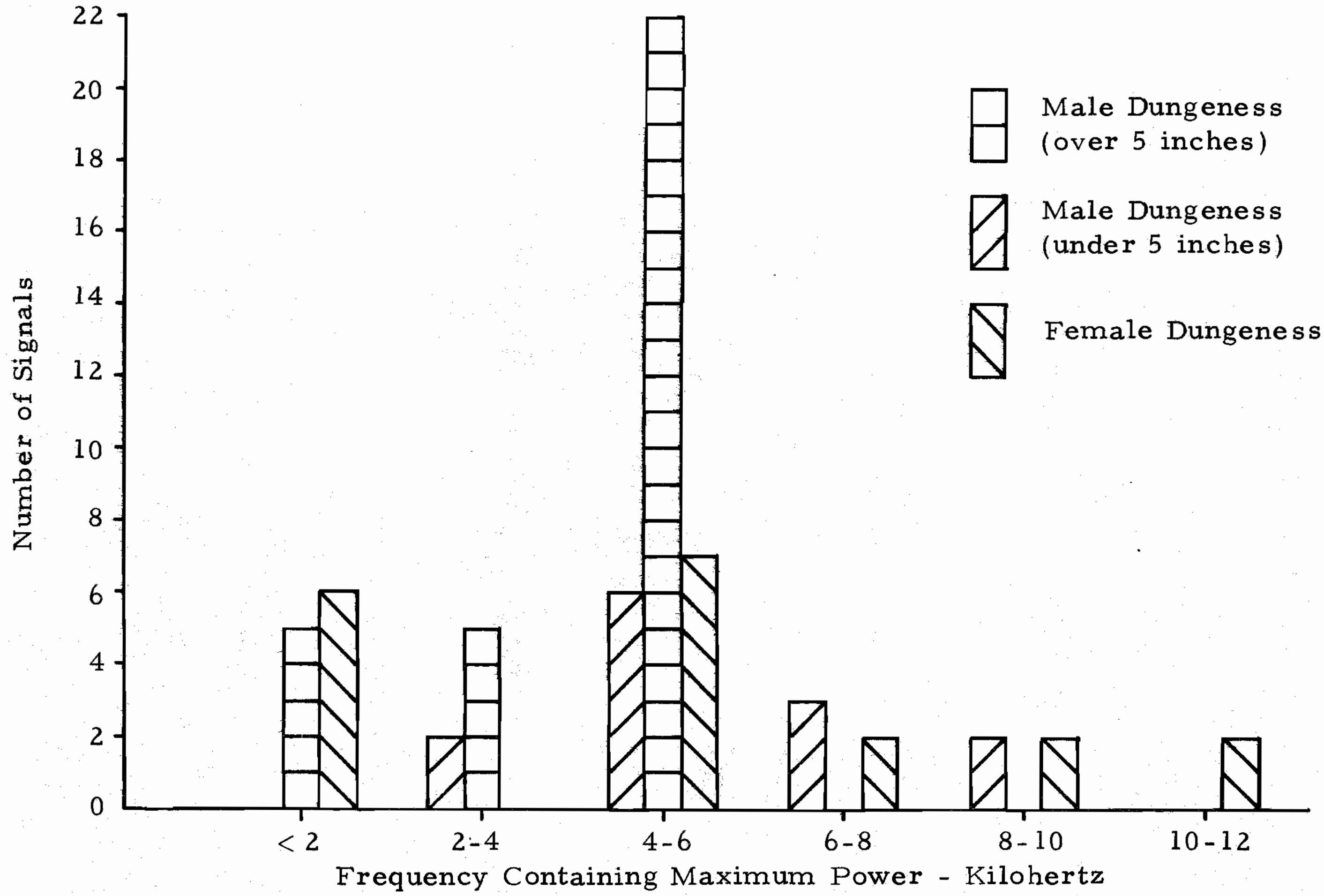


Figure 35. Distribution of frequencies containing maximum signal power in Dungeness crab signals.

crab signals contain peak power frequencies within this range in 46% of the signals. Female crab signals contain peak power frequencies within this range in 35% of the signals. The female crab signals also contain peak power frequencies of less than 2000 hertz in 30% of the signals.

The frequency containing the maximum amount of power in the power density spectrum of a given signal was compared with the same frequency as determined from the sonogram analysis. The frequency displayed on the sonogram can be read with an accuracy of ±10 hertz. When this figure is corrected by the scaling factor, the accuracy becomes, at best, ±320 hertz. In the estimation procedure the power density spectrums have been smoothed over a definite band width. Even with the deviations of the band width on the spectrograph and the band width of the window function, 68.4% of the frequencies containing maximum power determined from the power density spectrums were within 500 hertz of the values obtained from the sonograms. The comparisons agree within 1000 hertz in 80.0% of the signals, with the remainder differing by more than 1000 hertz.

V. CONCLUSIONS

The size of the samples, both number of crabs examined and number of crab signals obtained, prohibits drawing any statistical conclusions based on the data obtained in this investigation. Observations can be made, however, from the data, the results obtained from analysis, and the technique used in the investigation.

In examining signal duration times the limited amount of available computer core space must be considered. This factor influenced the selection of signals so that short signals were selected with greater frequency than were long signals. In some cases multiple signals were selected for analysis because the pattern they formed was repeated frequently by the crabs. As a result of these two factors, the maximum time duration signal (30 milliseconds) is not necessarily the longest signal recorded. Signals lasting one millisecond were expected, however the shortest signal detected was 2.8 milliseconds long. It is apparent from the data that the Dungeness and Japanese red rock crab signals have duration times ranging from about three milliseconds to 30 milliseconds, and possibly longer. It is not possible to identify the signals produced by a given species on the basis of signal duration times.

Prior to recording data for analysis purposes several signals were monitored to obtain an estimate of the required band width of the input filter. This investigation indicated an upper frequency of 15000 hertz would likely exceed the upper frequency of any signals of interest. The lower frequency limit of the filter was chosen as 800 hertz to permit filtering of ambient noises. However, varying the lower cut-off frequency between 200 hertz and 1000 hertz in the open bay recording session showed no signals of interest below 800 hertz.

Signals produced by Dungeness and Japanese red rock crabs were found to contain frequencies throughout the range of 800-15000 hertz.

The predominant type of autocorrelation function obtained for male Dungeness crab signals displayed nodal and anit-nodal behavior. This type of behavior also occurs in the female Dungeness crab signal's autocorrelation functions, but to a lesser degree. There appears to be a trend in the percentage of signals produced by male and female Dungeness crabs whose autocorrelation functions display nodal and anti-nodal behavior. The percentage of autocorrelation functions of male Dungeness signals displaying nodal and anti-nodal behavior is much larger than the percentage of autocorrelation functions of female signals displaying the same type of behavior. Further studies are necessary to determine the percentages for a larger sample. If the percentages for male and female crabs differ widely enough it may be possible to distinguish between sexes with a minimum of error.

The signals produced by Japanese red rock crabs also show the same type of behavior in their autocorrelation functions. However, there appears to be one major difference in the autocorrelation functions obtained from Dungeness and Japanese red rock crab signals. The time period between nodes in the autocorrelation functions of Japanese red rock signals is generally four milliseconds. The time period in the autocorrelation function of Dungeness signals is generally less than two milliseconds. If this time difference between nodes is a characteristic of a species' signal, it may be possible to identify the species which produces a signal by examining the autocorrelation function of the detected signal. Further investigation of a larger sample is necessary to determine if this is actually a characteristic of the species' signals.

The power density spectrums show a trend existing between the frequency containing the maximum power in a signal, and the sex of the Dungeness crab which produced the signal. Male signals tend to have frequencies containing maximum power between 4000 and 6000 hertz in 69% of the analyzed signals. The female signals tend to have frequencies containing maximum power in two ranges with 30% less than 2000 hertz, and 35% between 4000 and 6000 hertz.

The procedure used in this investigation can be readily adapted to handle a larger sample size in future studies. Refinement of the sampling program will allow the use of more computer storage space in which to store signals. The band width used in estimating the power density spectrum can be adjusted to provide any desired resolution of power peaks. This is possible since the band width is inversely proportional to the number of sample points, and therefore, is a function of the sampling frequency. The window width used in the estimation process can be refined to provide a greater accuracy of the estimate.

The results obtained from the data indicate that the technique used is a valid one. The values of the frequencies containing maximum power obtained from the power density estimation agree closely with those obtained from the spectral analysis. The conversion of the data to digital form and the use of a computer to perform the desired mathematical operations resulted in a minimal loss of information. The wide band width used in the power density estimation caused the loss of some information, but this can be controlled in future studies. There is no information lost in computing the autocorrelation function because this is a complete calculation, and not an estimate.

The area of the signal analysis which needs improvement is that of signal selection and data transfer. Visual selection of the signals and manual transferring of the signals is a time consuming process, and permits the possibility of obtaining biased signals. The technique will become more accurate and efficient when means are developed to aid human judgement in the selection and [illegible] transferring of signals.

The information gained from this investigation adds to the knowledge of the Dungeness crab. However, it also indicates that future studies are needed. A larger number of crabs needs to be studied in order to obtain data which is statistically meaningful. In any future studies the crabs should be isolated from contact with any solid surface to prevent contact noises. The actions of the crabs should be investigated to see if any correlation exists with the sounds produced. An investigation should also be made to see if a diurnal or a seasonal cycle exists in sound production. A long range investigation should be undertaken to study sound production and its changes, if any, through the life cycle of the Dungeness crabs.

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APPENDICES

APPENDIX I

APPENDIX I

Equipment characteristics and specifications

Transducer

Manufacturer:	Atlantic Research
Model:	LC-32
Sensing elements:	Lead zirconate titanate
Useful frequency range:	0.1 to 50,000 Hz.
Voltage sensitivity:	-102.2 db. (ref. 1 volt/Microbar)
Operating temperature range:	-60 C to +135 C

Transducer Preamplifier

Manufacturer:	Atalantic Research
Model:	LG-1364
Gain:	Rated at 40 db. Actual gain 39 db.
Frequency response:	Compatible with LG-32 hydrophone, flat over range of interest

AC Amplifier

Manufacturer:	Hewlett Packard
Model:	466A
Gain:	20 db. (X10) and 40 db. (X100) ±0.2 db. at 1000 Hz.
Frequency response:	±0.5 db. from 10 Hz. to 1 MHz.
Distortion:	Less than 1% from 10 Hz. to 100,000 Hz.

Filter

Manufacturer:	General Radio Company
Model:	Universal Filter Type 1952
Frequency range:	Adjustable from 4 Hz. to 60 KHz. In four ranges.
Filter characteristics:	A 4th order (four pole) Chebyshev approximation to ideal magnitude response.

Pass-band ripple:	±0.1 db.
Gain:	0 or -20 db., switch selected

Tape Recorder

Manufacturer:	Ampex
Model:	FR-1300 Recorder/reproducer
Number of channels:	14 using 1" tape
Tape speeds:	60, 30, 15, 7 1/2, 3 3/4, 1 7/8 ips.
Capstan speed accuracy:	±0.05%
Tape speed deviation:	±0.25%
Tape specifications:	1" tapes of 1 mil. polyester
Frequency response:	±1 db. from 0 to 20,000 Hz. at 60 ips., and ±1 db. from 0 to 625 Hz. at 1 7/8 ips.
S/N Ratio RMS:	46 db. at 60 ips., and 40 db. at 1 7/8 ips.

Oscillo-graph

Manufacturer:	Esterline Angus
Model:	0-291
Available speeds:	1, 5, 20, and 100 mm/sec. with 1% accuracy
Frequency response:	Flat from DC to 90 Hz. at 30 mm peak to peak deflection; down 3 db. at 125 Hz.

Audio and Sub-audio Spectograph

Manufacturer:	Kay Electric Co.
Number of channels:	2
Frequency range:	5-15,000 Hz. in 4 bands
Frequency response:	Switchable to provide flat response, ± 2 db. over entire range
Recording speed	10:1 on the 15-15,000 Hz. range

Recording time:	8 seconds on 15-15,000 Hz. range
Resolution:	6 or 60 Hz. using switchable filter on 15-15,000 Hz. range

APPENDIX II

APPENDIX II

Glossary

Ambient:	Surrounding on all sides; encompassing
Auto-correlation:	A mathematical operation. See appendix three for the mathematical definition.
Bias:	A tendency of a statistical estimate to deviate in one direction from a true value. See the mathematical definition in appendix three.
Broad-band:	Containing a broad band of frequencies.
Cephalothorax:	The united head and thorax of an arachnid or higher crustacean.
Crustaceans:	Any of a large class (Crustacea) of mostly aquatic arthropods having a chitinous or calcareous and chitinous exoskeleton.
Decapod:	Any of an order (Decopoda) of crustaceans with five pairs of thoracic appendages one or more of which are modified into pincers, stalked eyes, and the head and thorax fused into a cephalothorax and covered by a carapace.
Decibel (db):	A ratio of intensities or voltages expressed in logarithmic units. See appendix three for the mathematical definition.
Diurnal:	daily: happening each day
Hertz:	The new terminology for cycles per second.
Hybrid computer:	A computer composed of an analog computer, a digital computer, and an interfacing unit tying the two together.

Hydrophone:	A transducer which converts acoustic energy into electrical energy. It is not designed to transform electrical energy into acoustic energy, i.e. it is not reciprocal in nature.
Invertebrate:	Lacking a spinal column.
Kilo-:	prefix: meaning 1000.
Micro-:	prefix: meaning 1/1,000,000
Milli-:	prefix: meaning 1/1000.
Piezoelectric:	A material which acquires an electrical charge when placed under pressure, and acquires a stress when a voltage is applied to it.
Power density spectrum:	A plot of power vs. frequency.
Proprioceptive:	Of, relation to, or being stimuli arising within the organism.
Proprioceptor:	A sensory receptor excited by proprioceptive stimuli.
Quantitative:	Capable of being measured.
RB:	Research Boat
Sonic:	Having a frequency within the audible range of the human ear.
Stridulation:	The rubbing of parts of the body together.
Thorax:	The cavity in which the heart and lungs lie.
Transducer:	A device which transforms acoustical energy into electrical energy and/or transforms electrical energy into acoustical energy.
Transients:	A thing which passed quickly into and out of existence, i.e. voltages, currents, pressures, etc.
Variance:	Disagreement. See the mathematical definition in Appendix III.

APPENDIX III

APPENDIX III

Definitions

Bias: "Any statistic whose mathematical expectation is equal to a parameter θ is called an unbiased statistic for the parameter θ. Otherwise the statistic is said to be biased." (Hogg and Craig, 1965).

Variance: "Let $X_1, X_2, \ldots, X_n$ denote a random sample of size n from a given distribution,

the statistic

$$\overline{X} = \frac{X_1 + X_2, \ldots + X_n}{n} = \sum_{i=1}^{n} \frac{X_i}{n}$$

is called the mean of the random sample, and the statistic

$$S^2 = \sum_{i=1}^{n} \frac{(X_i - \overline{X})^2}{n} = \sum_{i=1}^{n} = \frac{X_i^2}{n} - \overline{X}^2$$

is called the variance of the random sample." (Hogg *et al.*, 1965)

$\sum_{i=1}^{n} \frac{X_i^2}{n}$ = The average value of the squared signal.

$\overline{X}^2$ = The average value of the signal squared.

Decibel: Number of decibels = 20 $\log_{10} \frac{V_2}{V_1}$

V_1 is often a reference voltage with a value of 1 volt (Lurch, 1962).

80% confidence limits: The limits within which there is an 80% chance the value will be.

Autocorrelation:

$$\phi_{11}(\tau) = \lim_{T\to\infty} \frac{1}{2T}\int_{-T}^{+T} f_1(t)f_1(t+\tau_1)dt$$

T = the period of the signal.

To evaluate the autocorrelation function it is necessary to form the function $f_1(t+\tau_1)$ by displacing $f_1(t)$ in time by the amount τ_1. Then the product of $f_1(t)f_1(t+\tau_1)$ is determined and the average of the product curve is obtained by integrating and dividing by the interval 2T. This average value is plotted against τ_1 and the process is repeated for a series of τ values. The result is an autocorrelation curve which is a measure of the similarity of a function $f_1(t)$ with itself when shifted by an amount of time τ (Lee, 1960). In the limit as $T \to \infty$, the equation becomes

$$\phi_{11}(\tau) = \int_{-\infty}^{\infty} f_1(t)f_1(t+\tau)dt$$

APPENDIX IV

APPENDIX IV

TABLES

Table I. Location of data for a given signal.

Type of crab	Signal number	Sonogram	Autocorrelation function	Power density spectrum
Male Dungeness	25	Fig. 4	Fig. 14	Fig. 25
(over 5 inches)	77	Fig. 5	Fig. 15	Fig. 26
	85	Fig. 6	Fig. 16	Fig. 27
Male Dungeness	31	Fig. 7	Fig. 17	Fig. 28
(under 5 inches)	36	Fig. 8	Fig. 18	Fig. 29
Female Dungeness	4	Fig. 9	Fig. 19	Fig. 30
	7	Fig. 10	Fig. 20	Fig. 31
	90	Fig. 11	Fig. 21	Fig. 32
Unidentified crabs	54	Fig. 12	Fig. 22	Fig. 33
	69	Fig. 13	Fig. 23	Fig. 34

Table II. Sampling frequencies used in data conversion.

Upper frequency limit (scaled by 32:1)	Sampling frequency	Samples/ hertz
300 hertz	1075 hertz	3.5
400 hertz	1430 hertz	3.6
500 hertz	1790 hertz	3.6
700 hertz	2500 hertz	3.6

Table III. Distribution of signal duration time.

Species	Total signals	Below 5 (milliseconds)	5-10 (milliseconds)	10-15 (milliseconds)	15-20 (milliseconds)	Over 20 (milliseconds)
Male Dungeness (over 5 inches)	34	5.3%	56.5%	20.6%	8.8%	8.8%
Male Dungeness (under 5 inches)	13	15.4%	69.2%	7.7%	0%	7.7%
Female Dungeness	21	19.0%	52.4%	19.0%	0%	9.6%
Male Red Rock	7	14.3%	85.7%	0%	0%	0%
Female Red Rock	8	0%	25.0%	0%	0%	75.0%
Unidentified	29	24.2%	51.7%	13.8%	10.3%	0%
Total sample	112	14.3%	55.4%	14.3%	5.3%	10.7%

Table IV. Distribution of autocorrelation wave shapes.

Species	Total signals	Type of autocorrelation function		
		Decaying sinusoid	Nodal and anti-nodal	Patternless
Male Dungeness (over 5 inches)	33	24.2%	66.6%	9.2%
Male Dungeness (under 5 inches)	13	23.1%	69.0%	7.9%
Female Dungeness	20	60.0%	25.0%	15.0%
Male Red Rock	7	71.5%	28.5%	0%
Female Red Rock	8	25.0%	75.0%	0%
Unidentified	30	73.4%	13.3%	13.3%

Table V. Power concentration of crab signals.

Species	Total signals	Power concentration		
		Single band	Double band	Triple band and above
Male Dungeness (over 5 inches)	32	62.5%	25.0%	12.5%
Male Dungeness (under 5 inches)	13	77.0%	15.3%	7.7%
Female Dungeness	21	65.0%	20.0%	15.0%
Male Red Rock	7	52.2%	28.6%	19.2%
Female Red Rock	8	75.0%	25.0%	0%
Unidentified	30	86.7%	10.0%	3.3%
Total sample	110	71.8%	19.1%	9.1%

Table VI. Signal characteristics.

Species	Signal number	Duration time (milliseconds)	Frequency range (hertz)	Half-power points (hertz)	Normalized power (watts)
Male Dungeness (over 5 inches)	10	23.4	800-3840 5440-7360	800-1200	1.820×10^{-6}
	11	14.3	800-3520	800-2550	1.312×10^{-6}
	12	6.2	800-11680	800-2300	1.987×10^{-5}
	14	12.5	1280-3200	1500-2850	2.380×10^{-7}
	15	6.5	2880-12480	3200-5300	6.832×10^{-7}
	16	16.5	1280-13440	3650-4500	3.809×10^{-6}
	17	10.0	1280-14720	3500-4900 7950-9300	1.957×10^{-6}
	18	15.0	960-10880	1600-3700	3.153×10^{-6}
	19	12.1	1440-12480	3600-4750	1.064×10^{-6}
	20	7.1	2560-9440	3200-5050	7.135×10^{-7}
	21	8.1	1280-10880	2900-6500	1.363×10^{-6}
	22	7.5	2240-15000	3000-5100 11000-11900	1.290×10^{-6}
	23	5.6	480-13760	2900-5400	8.485×10^{-7}
	24	15.9	3200-9280	1150-2450	4.516×10^{-7}
	25	26.5	800-8640	1300-1800	1.194×10^{-5}
	26	4.0	1920-7680	300-6750	7.458×10^{-7}
	27	14.0	2240-7360	4300-5700	5.748×10^{-6}
	28	8.7	800-4320	1150-2700	2.139×10^{-6}

Table VI. Continued

Species	Signal number	Duration time (milliseconds)	Frequency range (hertz)	Half-power points (hertz)	Normalized power (watts)
Male Dungeness (over 5 inches)	29	3.7	800-3200	800-3650	5.467×10^{-7}
	75	5.6	3200-9280	2900-5750	4.075×10^{-7}
	76	10.6	1280-8000	800-3950 5250-6850	3.054×10^{-8}
	77	6.2	2240-15000	3500-5500	8.404×10^{-7}
	78	6.5	800-15000	3200-11550	4.995×10^{-7}
	79	10.3	3200-15000	3750-5150 6050-7350 9450-11200	2.496×10^{-7}
	80	6.5	2240-15000	2750-5300	1.842×10^{-7}
	81	8.4	1600-15000	3450-5200	1.902×10^{-6}
	82	8.7	3200-13440	3600-5200	2.622×10^{-7}
	83	6.2	3200-13760	3300-7200	2.523×10^{-7}
	84	8.7	3200-13760	3550-5150 6400-6900 10000-11150	3.557×10^{-7}
	85	7.5	2880-15000	3500-5400	7.435×10^{-7}
	86	6.2	3360-5440	3200-5550	5.708×10^{-8}
	87	6.8	2880-12960	3300-5700	2.023×10^{-7}
Male Dungeness (under 5 inches)	30	22.5	960-8960 9760-15000	1600-2500	1.825×10^{-6}
	31	9.3	1280-15000	3450-4400	3.691×10^{-6}

Table VI. Continued

Species	Signal number	Duration time (milliseconds)	Frequency range (hertz)	Half-power points (hertz)	Normalized power (watts)
Male Dungeness (under 5 inches)	32	9.6	2560-15000	3150-3200 7100-11100	3.338×10^{-7}
	33	6.5	2400-13920	3200-5200	4.527×10^{-7}
	34	6.2	1440-9600 10560-15000	3150-5250	2.383×10^{-6}
	35	12.8	800-5440	2700-4000	4.546×10^{-7}
	36	9.3	2400-15000	3500-4900	9.045×10^{-7}
	102	5.9	1280-13120	3500-6500	3.795×10^{-7}
	103	5.3	960-15000	4600-8200	1.128×10^{-6}
	104	3.1	1440-13440	2850-12000	1.477×10^{-7}
	105	5.9	1600-11520	3000-6000	9.693×10^{-8}
	106	6.2	5120-15000	7600-10000	3.740×10^{-7}
	107	4.6	3520-12160	4500-8650	1.220×10^{-7}
Female Dungeness	1	20.9	2560-15000	800-1550	1.557×10^{-6}
	2	21.9	2240-15000	3500-3800 10200-11000	2.261×10^{-6}
	3	7.8	800-6720	800-2400	3.700×10^{-6}
	4	12.2	800-5760	950-2150	5.350×10^{-6}
	6	10.9	800-15000	800-4850	6.411×10^{-7}
	7	9.0	800-4160	800-1800	6.838×10^{-6}
	8	9.3	800-5760	800-1600	5.902×10^{-6}

Table VI. Continued

Species	Signal number	Duration time (milliseconds)	Frequency range (hertz)	Half-power points (hertz)	Normalized power (watts)
Female Dungeness	88	7.5	4160-15000	4000-7100 7750-9400	1.572×10^{-7}
	89	10.9	3200-13760	Rejected by the computer	
	90	5.9	3200-7040	3150-5700	1.157×10^{-7}
	91	6.2	3200-13120	3000-6100 9750-10900	7.356×10^{-8}
	92	7.8	3200-13120	3400-5300	1.225×10^{-7}
	93	10.9	3200-14720	3600-4300 5400-7200 9950-11200	1.020×10^{-7}
	94	7.8	1600-13440	3400-7000	5.503×10^{-7}
	108	2.8	5120-15000	4750-11850	1.909×10^{-7}
	109	5.0	800-14400	3600-7100	3.202×10^{-7}
	110	5.9	960-13120	4300-7900	1.146×10^{-6}
	111	2.8	5440-15000	6700-13100	2.260×10^{-7}
	112	6.5	1600-9920	2900-8500	8.776×10^{-8}
	113	2.8	800-12960	2300-9650	4.047×10^{-7}
Male Red Rock	95	5.6	1280-13440	4000-7700	3.694×10^{-7}
	96	5.0	2240-14080	4750-9200	3.018×10^{-7}
	97	5.3	4480-11840	4300-11200	7.528×10^{-8}
	98	9.3	1600-12160	5600-7200	3.003×10^{-7}

Table VI. Continued

Species	Signal number	Duration time (milliseconds)	Frequency range (hertz)	Half-power points (hertz)	Normalized power (watts)
Male Red Rock	99	7.5	800-14720	3600-6900 7850-11500	$7.830 \mathrm{x} 10^{-8}$
	100	7.1	3520-11520	3400-6500	$1.264 \mathrm{x} 10^{-7}$
	101	7.1	1280-13120	5600-7600	$4.864 \mathrm{x} 10^{-7}$
Female Red Rock	37	30.0	800-3520	1450-2100	$1.413 \mathrm{x} 10^{-5}$
	38	25.3	800-15000	5450-6200	$8.648 \mathrm{x} 10^{-6}$
	39	9.6	3520-13760	5200-9100	$8.309 \mathrm{x} 10^{-7}$
	40	21.5	800-11200	1500-2100	$9.350 \mathrm{x} 10^{-7}$
	41	10.0	3520-5760 14080-15000	3600-5000	$1.326 \mathrm{x} 10^{-7}$
	42	22.5	800-7200 8960-10400	1400-2100	$1.597 \mathrm{x} 10^{-6}$
	43	20.9	800-7040	1400-2100	$1.362 \mathrm{x} 10^{-6}$
	44	24.6	800-3520	1450-2050	$3.821 \mathrm{x} 10^{-7}$
Unidentified	45	7.8	800-4480	800-1600	$6.746 \mathrm{x} 10^{-6}$
	46	10.0	3520-6720	800-1600	$3.197 \mathrm{x} 10^{-7}$
	47	17.1	800-3200	800-1600	$1.170 \mathrm{x} 10^{-6}$
	48	12.8	800-1920	800-1500	$3.191 \mathrm{x} 10^{-7}$
	49	7.1	800-15000	800-4600 10400-14150	$3.344 \mathrm{x} 10^{-7}$
	50	3.4	800-15000	7500-11900	$1.317 \mathrm{x} 10^{-6}$

Table VI. Continued

Species	Signal number	Duration time (milliseconds)	Frequency range (hertz)	Half-power points (hertz)	Normalized power (watts)
Unidentified	51	6.2	960-6400	1100-3500	$3.488\text{x}10^{-7}$
	52	3.7	3360-12800	800-2900	$8.787\text{x}10^{-8}$
	54	19.3	800-10720	1100-2000	$1.594\text{x}10^{-5}$
	55	8.4	800-15000	12200-14350	$2.340\text{x}10^{-6}$
	56	5.0	960-3200	800-3200	$2.244\text{x}10^{-7}$
	57	9.6	800-2560	800-1900	$2.658\text{x}10^{-7}$
	58	5.3	800-3520	800-3600	$2.430\text{x}10^{-7}$
	59	5.3	800-1600	800-1800	$6.930\text{x}10^{-8}$
	60	6.2	1920-4800	1550-4050	$2.776\text{x}10^{-8}$
	61	5.3	800-3520	800-2000	$4.188\text{x}10^{-6}$
	62	4.6	800-6080	800-2850	$4.441\text{x}10^{-6}$
	63	13.7	800-10560	800-1450	$5.956\text{x}10^{-7}$
	64	4.3	800-3840	800-2000	$4.389\text{x}10^{-6}$
	65	7.8	800-15000	1000-4300	$1.590\text{x}10^{-7}$
	66	11.5	960-5120	1100-3700	$3.953\text{x}10^{-8}$
	67	5.9	960-2240	800-2700	$3.305\text{x}10^{-8}$
	68	4.0	1600-3200	800-4100	$2.919\text{x}10^{-8}$
	69	16.5	800-15000	1500-2250	$8.396\text{x}10^{-6}$
	70	10.3	800-2560	800-2100	$8.521\text{x}10^{-8}$
	71	2.8	800-4800	800-3750	$9.818\text{x}10^{-8}$

Table VI. Continued

Species	Signal number	Duration time (milliseconds)	Frequency range (hertz)	Half-power points (hertz)	Normalized power (watts)
Unidentified	72	8.1	800-6080	-2000	9.647×10^{-8}
	73	5.6	800-15000	-5400	4.332×10^{-7}
	74	8.1	800-10880	1050-5200	1.904×10^{-7}

Values in the table which read exactly 800 hertz or 15000 hertz are not meant to imply that no frequencies exist either above or below these points. Any frequencies present outside the range of 800-15000 hertz could not be determined accurately due to the filtering process employed during the recording of the signals.