ANALYSIS OF THE VOCALIZATIONS OF *ORCINUS ORCA* IN RESPONSE TO ANTHROPOGENIC NOISE

A

THESIS

Presented to the Faculty

of the University of Alaska Fairbanks

in partial Fulfillment of the Requirements

for the Degree of

MASTER OF SCIENCE

By

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Fairbanks, Alaska

May 2000

Abstract

Underwater noise created by vessel traffic in the world's oceans may be detrimental to marine life that relies on acoustic senses for survival. An analytical study was completed which examined changes in vocal behavior of subpod A36, killer whales (*Orcinus orca*) that reside off Vancouver Island. The average call rate of each call type was calculated from the recordings, and call rates were found to significantly decrease in the presence of vessel noise. Structural characteristics of specific call types such as differences in frequency, duration, and harmonics were also examined and statistically compared with and without boat noise. Differences found include a decreased number of harmonics in the N5 call, and a more peaked distribution of the average frequency of the first harmonic of the N4 call when associated with vessel noise. The significance of the result relative to the possible disturbance of these killer whales is uncertain.

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Chapter 1

Introduction

Public interest in environmental health has increased greatly in the last thirty years, in part due to greater awareness of the effects of the rapidly increasing human population and the desire to lessen the negative impacts this may have on wildlife. Since the industrial revolution, human-made noise in the ocean has increased tremendously, and has in fact become the most significant source of low-frequency noise in the ocean [*Ross*, 1976]. Sound, unlike light, is transmitted extremely efficiently through water, and the noise created by ship and boat traffic and other human activities can be detected at great distances from the source. These rising ambient noise levels over the years have caused growing concern that noise from human activities could have negative effects on marine mammals. Those concerned include scientific, government, and conservation organizations, indigenous peoples, and increasingly, the general public. If loud enough, noise can produce a variety of physiological damage in marine life, affecting the auditory and central nervous system, and even inducing symptoms of stress [*Kryter*, 1985; *Ketten* et al., 1993; *Kastak* et al., 1998; *Seyle*, 1973; *Ames*, 1978; *Jensen and Rasmussen*, 1970; *Arguelles* et al., 1970; *Friedman* et al., 1967; *Rosen*, 1970; *Rosencrans* et al., 1966; *Franklin and Brent*, 1964; *Senger* et al., 1967]. Of the many possible effects of noise on marine mammals, potentially one of the most detrimental is interference with their acoustic senses.

Marine mammals obtain much information about their surroundings by the use of sending and receiving sound. Acoustics are used by various marine mammals to contact members of a social group, to aid in navigation, in the detection and capture of prey, and to communicate messages such as distress or danger. Not only is it possible that noise affects, at least temporarily, the hearing abilities of marine mammals, but it may also inhibit sound production and reception by reducing the range of transmission. Noise could interfere with the mammals' ability to receive signals from conspecifics or even impede the reception of their own echolocation.

In most studies looking at the effects of boats and boat noise on free-ranging cetaceans, researchers have examined surface behavior such as respiration rates, swim speed, path of travel, and other erratic behaviors [*Baker* et al., 1982; *Blane*, 1990; *Brodie*, 1981; *Kruse*, 1985, 1991; *Lockyer*, 1977; *Malme* et al., 1989; *Reeves*, 1992; *Stewart* et al., 1982; *Williams*, 1999]. Compared to surface behavior studies, relatively few researchers have examined the effects of noise on the vocal behavior of cetaceans. The effects of boat noise on humpback whale (*Megaptera novaeangliae*) vocalizations were studied by *Norris* [1994] off the coast of Hawaii. Humpbacks decreased their song unit durations and changed some frequency structures of their song units. Norris suggested that this may indicate disturbance in the singing whales.

In the study of beluga (*Delphinapterus leucas*) vocalizations by *Lesage* et al. [1993], call types, rates, and frequencies changed when the whales were approached by a boat. Increasing the mean frequency bands appeared to be a strategy to increase the detectablity of the signal above the noise. This and the fact that belugas have been seen rapidly leaving areas that contain fast and erratically moving boats [*Blane*, 1990] demonstrates that the belugas are probably disturbed by the boat noise.

Dahlheim et al. [1984] and *Dahlheim* [1987] looked at grey whale (*Eschrichtius robustus*) vocalizations in the presence of boat noise and found that vocalization rates increased. This vocal change also could be an indicator of disturbance. No known injury or damage from this type of low level noise has been documented. However, since the long-term consequences of these possible disturbances are unclear, it is important to continue research to better understand how these animals are affected in ways that might impair their long-term well-being.

A comparison of individual killer whale (*Orcinus orca*) calls from a single subpod from the northern resident orca community off British Columbia is the focus of this study. The boat traffic is very active in the waters in which these whales live in the summer months, including ferries, barges, sport and commercial fishing vessels, tour ships, and whale-watching vessels. Often, if a pod of orcas is in the area, the vessel operators will communicate the pod's whereabouts to each other, and it is not uncommon to see a pod surrounded by several interested vessels. It is conceivable that killer whales alter characteristics of their vocalizations when in the presence of strong vessel noise. By examining the call rates and call spectral structures, it should be possible to determine if the whales change some aspect of their calls in order to reduce the effects of noise or simply as a reaction to the strong vessel noise.

The specific objectives of the work presented in this thesis are:

(i) Compare the call rates of the different call types from recording samples taken with and without boat noise.

(ii) Analyze spectral characteristics of four call types, N4, N5, N1, and N7, in order to observe if they change while in the presence of boat noise. Spectral characteristics studied include: average frequency of the first harmonic, number of harmonics, duration, duration of first section of the call, and peak duration. These characteristics are discussed further later.

(iii) Analyze vessel noise, specifically looking at the signal to noise ratio.

An overview of the killer whale is presented in Chapter I, with information on its biology and vocalizations. Distribution and morphology are discussed, as well as visual identification methods, habits, and social behavior. There is an overview of types of vocalizations, their purpose, and vocal dialects. This chapter also discusses killer whale sound production and reception. Chapter II is titled 'Acoustics', and gives an introduction to underwater sound. There are sections on the sonar equation, and some brief information on sound measurement units. The section on sound analysis explains what a spectrogram is, and the method used to create the spectrograms. This method is useful in taking a sound wave and making it into a visual representation showing frequency, time, and amplitude. Noise is also discussed in this chapter, explaining types of noise, sources of noise, why the signal to noise ratio is important, and some effects of noise on marine mammals as shown from past research. Noise can cause masking of the signal, contributing to problems in signal reception and communication. It can also cause behavior disruptions in marine mammals and physiological and psychological damage. Last, there is a section discussing some noise reduction adaptions that orcas can use to reduce the negative effects noise may have on their communication. Chapter III describes the methods and analysis in this research. In Chapter IV, the results of the analysis are given. Chapter V is a discussion of the results of the study. This last chapter also gives a detailed discussion of the limitations of this study, and improved methods for future studies.

In a species such as the killer whale, where vocalizations are complex and vocal behavior is an important method of intraspecies communication, acoustic disruption from loud and frequent noise is likely to have deleterious effects on the health of the population. For example, continuous disruptions in the whale's communications involving perhaps location of food, or location of individuals, and efforts to keep the subpod together may result in energetic consequences. These effects may be gradual, thus it is important to continue studies in order to understand all the complexities involved. By comparing specific structural differences in the spectra of individual discrete calls, this study could contribute a better understanding of killer whale vocal behavior, specifically to vocal changes in the presence of boat noise.

Chapter 2

The Killer Whale

2.1 Killer Whale Biology

The killer whale, like all whales, belongs to the taxonomic order Cetacea. Whales evolved along two very different lines, the odontocetes or toothed whales, and the mysticetes, or baleen whales. Killer whales, which are actually more closely related to dolphins and porpoises than to the other whales, are odontocetes, and are the largest member of the Delphinidae family.

Killer whales are distributed worldwide, and are found in all of the world's oceans [*Leatherwood and Dahlheim*, 1978]. They are found in water ranging in temperature from cold, polar waters to warm, tropical waters, however they are most likely to be found in colder inshore or shelf waters [*Leatherwood and Dahlheim*, 1978]. Their movement seems to be related primarily to movements of their food supply.

The coloration of killer whales is very distinct. Their dorsal side is black, and their

Figure 2.1: The Killer Whale. Photo of a killer whale, *Orcinus orca*, breaching. This photo shows the killer whale's easily recognizable black and white pattern.

ventral surface has a distinctive black and white pattern (See Figure 2.1). Above each eye is a white patch, and behind the dorsal fin is a lightly pigmented saddle patch. Sexual dimorphism in killer whales is seen in the overall body size as well as the appendage size. The adult male killer whale is larger than the female, with males averaging 8.2 m in length, and possibly weighing over 8 tons, while females average 7 m, and rarely weigh more than 4 tons [*Nishiwaki and Handa*, 1958; *Jonsgard and Lyshoel*, 1970].

The dorsal fin is smaller and more curved, like that of a dolphin, in the females and juvenile males, while tall and triangular in the adult male. In an adult male the dorsal fin may be 1.5 to 2 m taller than that of the female [*Ivanova*, 1961]. Figure 2.2 is a photo

photo by C. Talus

Figure 2.2: Dorsal Fin Size Differences. The differences in size of the dorsal fin between adult male and female orcas. The adult male's dorsal fin is much taller and straighter, while the female's is smaller and more curved.

showing the size difference in dorsal fins. Their flippers are rounded and broad in shape, and are also much larger in the adult male than the female. Coloration in the genital area also differs for males and females [*Bigg*, 1987].

This study investigates orcas found in the nearshore waters along British Columbia's coast. These orcas have been studied extensively. Longterm field studies, which continue today, began in the 1970's to study the behavior of these wild killer whales. As soon as it was discovered that individual killer whales could be identified from photographs taken in the field [*Bigg*, 1982], researchers then began gaining a much greater understanding of these cetaceans, because life histories could be reliably documented for the first time. The

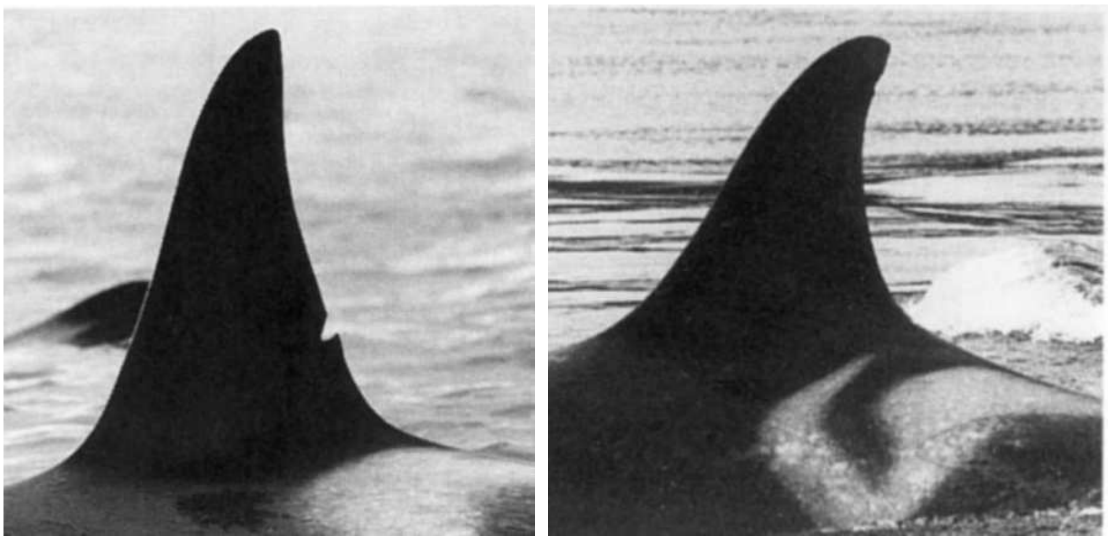

Figure 2.3: Identification Photos of D9 and J1. These photos from *Ford* et al. [1994] of the dorsal fins of D9 and J10 show some of the differences in dorsal fins due to shape and irregularities and also differences in the saddle patches. These differences are how individual whales can be identified by researchers.

orcas are identified by distinctive characteristics on the dorsal fin and saddle patch, such as shape, coloration, size, and irregularities. Figure 2.3 taken from *Ford* et al. [1994] is of photos of two individual whales, D9 and J10. These photos show some of the differences that are obvious in the dorsal fin and saddle patch. Because killer whales are so large, it is relatively easy for a researcher to identify those whales with dorsal fin injuries or unusually shaped saddle patches with binoculars or a spotting scope. Identification photographs of individual whales have been cataloged for the British Columbia whales [*Ford* et al., 1994]. This method of visual identification has been invaluable as an unobtrusive way to study these orcas year to year.

The orca populations that live off the British Columbia inshore coast have been classified into two types of groups, resident and transient killer whales [*Bigg*, 1987]. These groups differ in behavior, morphology, eating habits, and vocalizations [*Balcomb* et al., 1982; *Bigg*, 1982, 1987; *Bain*, 1988; *Ford*, 1987; *Olesiuk* et al., 1990]. Transient and resident killer whales can be visually distinguished from each other by differences in their dorsal fin and saddle patch. The resident dorsal fin tip is smoother, the overall dorsal fin shape is more rounded or curved, and the saddle patch may contain various amounts of black. Transients typically have a pointed dorsal fin (this is especially seen in adult females) and a large, uniformly colored saddle patch. A very important difference between the two groups is diet. Residents eat primarily fish, while transients prey on marine mammals. In fact, residents seem to ignore marine mammals, while transients ignore fish [*Ford* et al., 1994]. Besides being efficient marine mammal predators, transients have a very different social structure. Transient groups are more fluid, and tend to be much smaller [*Ford* et al., 1994]. Also, transients are less predictable in their behavior, are seen less frequently, do not appear to have a well defined range, and roam greater distances [*Ford* et al., 1994]. While hunting, transient killer whales are completely silent, perhaps to avoid warning their marine mammal prey of their approach. It is also interesting to note that transients and residents are socially isolated from each other, with the two groups not associating with each other.

Resident killer whales are more predictable in their behavior, and are commonly seen in the summer months when salmon are most abundant. They are extremely vocal, producing echolocation clicks used to navigate and forage, and many unique sounding vocalizations used in communication. Resident orcas are very social, and are found in groups typically between 5 and 20 animals. These groups of orcas have stable memberships which is in part due to their low mortality and birth rates, so the composition of the groups may show little change over periods of many years. *Bigg* et al. [1990] has defined these matriarchal groups of resident orcas depending on how much time they spend together. The smallest group of orcas is called an intra-pod. Intra-pods are matrilineal and an individual is rarely separated from this group. Groups of orcas that spend greater than 95 percent of the time traveling with each other are called subpods. Subpods are composed of 1-11 matrilineal groups. Pods are composed of 1-3 subpods and travel together over 50 percent of the time. The resident orcas of British Columbia are divided into two communities, the southern and the northern residents. The southern community consists of the J, K, and L pods, which have about 80 whales total. Their range is south of Discovery Passage in the inshore Vancouver Island waters. The northern resident community consists of 16 pods, A1, A4, A5, B1, C1, D1, H1, I1, I2, I18, G1, G12, I11, I31, R1, and W1, with a total of about 135 whales. This community is found north of Discovery Passage.

2.2 Killer Whale Vocalizations

Sound is the most efficient way for cetaceans to communicate over long-range distances underwater, and is also useful at near distances. Although acoustic signals are often not as directionally precise as visual signals, clicks and some high-frequency sounds can be very directional. An omnidirectional signal can be useful for an orca when calling to dispersed members of its pod. Orcas have three kinds of acoustic signals: clicks, whistles, and pulsed calls.

Clicks are short pulses which contain energy over a wide range of bandwidths. These are usually given in a series and are used as echolocation for orientation and prey capture [*Awbrey* et al., 1982]. Clicks are composed of both a high and a low frequency component with the high frequency component being highly directional [*Schevill and Watkins*, 1966]. Clicks have been recorded by *Ford and Fisher* [1982] with repetition rates of 1 or 2 clicks to over 300 clicks per second, with frequencies as high as 35 kHz. *Diercks* et al. [1973] recorded click frequencies as high as 85 kHz and durations of clicks ranging from 0.1-25 ms. Whistles are tonal signals with a continuous waveform. *Ford and Fisher* [1982] present a spectrographic example of a whistle showing little or no harmonic structure. *Ford* [1984] recorded whistles at frequencies of 1.5-18 kHz with durations ranging from 50 ms to 10-12s. The most common orca vocalization is the pulsed call. These calls are made up of individual clicks that are rapidly repeated at an increased rate [*Schevill and Watkins*, 1966]. The result is a scream-like sound that can be extremely variable and is rich in harmonics. The clicks that make up pulsed calls can have repetition rates of up to 4000/s or more, with most energy between 1-6 kHz and call durations usually between 0.5-1.5 s long [*Ford and Fisher*, 1982]. *Ford* [1989] classified pulsed calls into three types: discrete, variable, and aberrant. They classified discrete calls as those that have distinct structural properties, are highly repetitive, and can easily be assigned to different, distinctive call types. Most pulsed calls are discrete calls. Variable calls are signals that cannot be clearly defined and can range widely in sounds. These calls are not repetitive. Finally, they classified aberrant calls as those that are modified or distorted versions of discrete calls. Often, when the whales are excited, they emit a kind of discrete call that is classified as 'excited'. These excited calls tend to have an increase in pitch. Calls are named with an alphanumeric system. Calls start with 'S' if from the southern community, and 'N' if from the northern community, and are numbered in the order in which they were first classified. In this study, only pulsed discrete calls are examined.

Killer whales have structurally distinct vocal signals, or dialects, among the different social groups [*Ford and Fisher*, 1982; *Ford*, 1984, 1987, 1989, 1991; *Strager*, 1995]. *Ford* [1989] notes that killer whale dialects differ among different social groups, which is interesting because these groups do associate and socialize together. Thus, their dialects are not necessarily due to geographic differences. Two pods with similar dialects may be more closely related and perhaps originated from the same ancestors [*Ford and Fisher*, 1982; *Deecke*, 1994]. The northern resident community of orcas in the study area have a vocal repertoire of 7 to 17 discrete call types [*Ford*, 1989]. These structurally unique calls are passed down to next generations through copying and vocal learning [*Deecke*, 1994; *Ford*, 1989, 1991; *Bain*, 1986, 1988].

The acoustic dialects of the distinct killer whale groups are very stable, and are useful when studying these whales because the pod may be identified acoustically when it is difficult or impossible to identify them visually. It should be noted that these dialects, although extremely stable, are subject to slight variation over very long lengths of time (12 years), although only for certain call types [*Deecke*, 1994]. Orcas may have these distinct dialects for many reasons. They are very active in their behaviors and spend much of their time foraging for food in the waters where they live, as well as socializing with other groups of orcas. Many of their activities could cause them to become dispersed from each other. *Ford* [1991] suggests that killer whales may have evolved to have these group-specific dialects as a way to keep the family group in acoustic contact. This ensures that they can keep track of each other or even coordinate group activity.

2.3 Killer Whale Sound Production and Hearing Ability

Cetaceans evolved from mesonychid condylarths, a small terrestrial carnivore [*Lipps and Mitchell*, 1976] which eventually became amphibious, and returned completely to the sea. Thus, whales have an inner ear similar to a land mammal's air-adapted ear. When evolving back to life in the ocean, basic functions had to be accomplished in water, an often indistinct environment. It is not surprising then that sound became the central sensory and communication system for cetaceans.

2.3.1 Sound Production

Bradbury and Vehrencamp [1998] give three steps in sound production: production of vibrations, modification of the vibrations, and coupling of the vibrations to a propagation medium. Odontocetes successfully accomplish these three steps. In order to effectively produce long-ranging and directional sounds underwater, odontocetes had to adapt a unique way of transmitting sound. Up until fairly recently, there have been two popular theories for the location of sound production in a cetacean: the larynx and the nasal sac system.

The larynx is the primary source of sound in most other mammals, and odontocetes do have a sophisticated larynx. However, evidence rules out the larynx as the source of sound production in an odontocete. For example, various studies have shown movement in the nasal system, while none was seen in the larynx during sound production [*Hollien* et al., 1976; *Mackay and Liaw*, 1981; *Dormer*, 1979; *Ridgeway* et al., 1980]. Most likely, sound is produced within the nasal sac system of odontocetes.

Below the blowhole, the nasal canal divides, with each of the two nasal passages having a nasal sac and a muscular nasal plug which can close or constrict the passage. The passages then join into one canal which passes through the larynx and pharynx to the lungs. The air trapped in the sacs, trachea, and lungs is moved between these areas to create vibrations in small membranes in the sacs [*Cranford*, 1992]. The exact method is poorly understood, but the idea is that air is forced through the nasal passages, which creates sound. *Au* [1993] speculates that the actual sound-producing method is either air blowing across a vibrating membrane or orifice, or into a resonating chamber, or by the mechanical motion of some structure rubbing against another. Several methods of sound generation are discussed in detail by *Cranford* [1992].

The sound is then focused through the fatty melon on the odontocete's head. The odontocete's skull and air sacs reflect the sound produced to the melon. The melon is composed of translucent oil and picks up sound and helps focus it into a forward beam [*Aroyan* et al., 1992]. Because the tissue of an odontocete has an acoustic impedance similar to that of water, the oil is necessary to confine and focus the sound beam formed

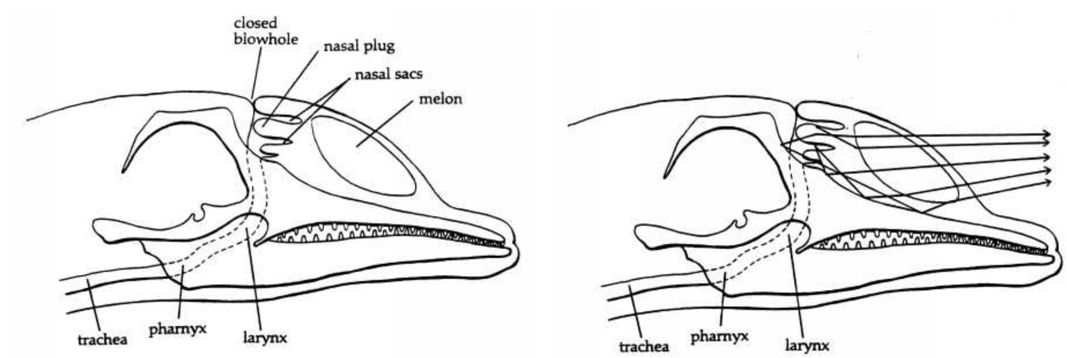

Figure 2.4: Anatomy of Odontocete Cranium. The anatomy of an odontocete head pertaining to how sound is produced and transmitted. Sound is created by air being forced through the nasal passages. The skull and air sacs reflect sound to the melon, where it is focused into a beam. Illustration taken from *McNally* [1977].

by the skull and air sacs, and provides a gradual impedance match between the animal and medium. This oil actually is used to couple the acoustic energy from the whale to the water. Figure 2.4 shows the basic anatomy of an odontocete head, and how sound is directed from the melon.

2.3.2 Sound Reception

The hearing ability of cetaceans is highly discriminating and sophisticated. This can be proved by their many, complicated communication sounds as well as by their use of echolocation. The odontocete's ear is composed of the same basic parts of any mammal's ear. Sound vibrates the three small bones, or ossicles, to send vibrations to a membrane in the fluid filled cochlea. The waves in the fluid trigger hairs cells which are tuned for specific frequencies, and these impulses are picked up by the auditory nerve which then sends this information to the brain. In a study on the cochlea of dolphins, *Wever* et al. [1971] found that the long cochlea of an odontocete as well as the large numbers of hair cells are suggestive of a high level of auditory capability and a high degree of frequency discrimination. Additionally they found that the ratio between ganglion cells and hair cells in an odontocete to be a little over 5 to 1, while in the human ear, this ratio is about 2 to 1. This suggests that the odontocete either requires more neural pathways for the transmission of the high frequency information, or that the odontocete's neural system presents more details to the brain than a human's does. One problem cetaceans had to deal with when adapting to underwater hearing was keeping bone conducted sound out. This problem was solved by isolating the ear from the skull. The two bones that encase the ear do not touch the skull. One is suspended by a ligament, and the other rests on blubber. Another way in which they have adapted for hearing underwater is by changing the way in which sound reaches their ear bones. Instead of the ear canal, sound reaches the inner ear through the lower jaw [*Norris*, 1968]. The posterior end of the jaw is filled with fat, and there are fat deposits extending out from the jaw to the skin and throat. This fat carries sound waves in to the ear of the whale, so that the jaw acts as a receiver for sound waves.

The sensitivity of an animal to sounds of different frequencies is shown by an audiogram. Audiograms are obtained either by behavioral tests on captive animals, or by electrophysiological tests on the nervous system. An audiogram shows an animal's absolute auditory threshold at each frequency. The absolute auditory threshold is the minimum received

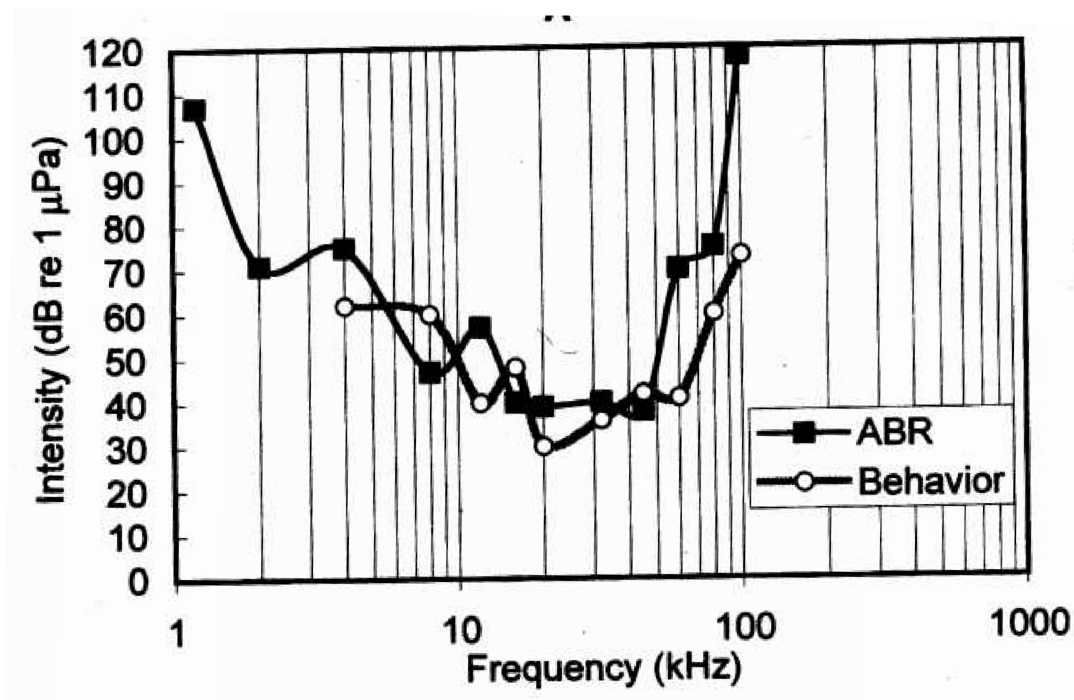

Figure 2.5: Audiogram of Killer Whale. An audiogram for a killer whale. This figure is taken from *Szymanski* et al. [1999].

sound level at which a sound with a particular frequency can be heard. Fortunately, the auditory brainstem response (ABR) audiogram is now possible as a noninvasive, extracranial technique [*Ridgeway* et al., 1981]. Recently, killer whale audiograms have been measured in two adult females using this technique [*Szymanski* et al., 1999]. Figure 2.5 shows the hearing sensitivity curve for one of these animals. The whales were found to have the best hearing threshold in their most sensitive range of 18-42 kHz, and the least threshold at higher frequencies of 60-100 kHz. The most sensitive frequency in the audiogram was found to be 20 kHz, which matches the peak levels for an orca's echolocation clicks. Other data shows the upper frequency limits near 120 kHz for a killer whale [*Bain* et al., 1993]. Data from this audiogram suggests that the killer whale's hearing sensitivity at low frequencies is quite poor. However, *Turl* [1993] suggests that they may be more sensitive to a combination of pressure fluctuations and low frequency particle motion when in the near-field of the acoustic source. In contrast, the killer whale's hearing at middle frequencies is very acute, and at high frequencies it is exceptionally good.

Chapter 3

Background Acoustics

The act of communicating involves transmission of a signal through some medium to a receiver. In water, sound is the most efficient way to send and receive a signal. Sound is caused by a mechanical disturbance in an elastic medium (air, liquid, or solid) which creates a wave motion propagating in that medium. Sound waves can be described as fluctuations in pressure propagating away from the sound source with a certain velocity. Sound, unlike light, can go through opaque barriers, such as the silty waters surrounding a glacier. Sound can bounce off objects with little loss in energy, and can propagate over a considerable range to stimulate the mechanoreceptors of the auditory system. Sound is so important that all vertebrates use sound for survival. Sound is different from other forms of sensory stimulation because it provides information at larger distances. Sounds can be used to detects and communicate the approach of an unsuspecting prey, a member of the same species, or some form of danger. Sound, especially from echolocation as used by cetaceans and bats, can give important information on an animal's surroundings. Animals most likely adapted to use sound because it enables them to respond to events outside their immediate environment, and to take the appropriate action. Cetaceans have evolved to use sound as a form of vision and communication, which is ideal because the waters in which they live can sometimes be dark, cloudy, or turbid. Since acoustic energy propagates much more efficiently in water than other forms of energy, the use of sound by marine mammals is an excellent way to communicate and navigate.

3.1 Introduction to Underwater Sound

A propagating sound wave, such as the sharp call of an orca or the distant hum of boat noise, consists of alternating compressions and decompressions in the medium the wave travels through. As a wave of sound energy travels through the water, the fluid particles vibrate generating pressure disturbances. This sound wave is detected by the receiver as changes in pressure. No single molecule moves along, instead it is the disturbance that is propagated to greater distances, as one vibrating molecule layer collides with another layer, causing it to collide with a third layer, and so on.

The characteristics of a sound wave are amplitude, wavelength, and frequency. An orca call may sound louder or softer due to changes in amplitude. The amplitude is proportional to the maximum distance a vibrating particle is displaced from its resting state. The amplitude can be thought of as the pressure of the wave. Amplitude, also known as intensity, is often measured in terms of decibels (dB). The decibel scale is a ratio of power or energy.

Decibels are used as a measure of sound pressure levels for two reasons. First, the decibel system is a logarithmic system, which is convenient for dealing with very large changes in quantities. Second, it is designed to mimic human hearing which is also logarithmic. A vertebrate ear may be able to detect sounds whose pressures vary over a 100,000 fold range [*Bradbury and Vehrencamp*, 1998]. If the amplitude of sound is increased in equal steps, our ears perceive the loudness of the sound to increase at each step, but we perceive the increase to be smaller than the one before. In addition to being ranked logarithmically, the decibel scale is a relative scale. This means that a certain sound amplitude is not a certain value in decibels, but it is given a value relative to some standard reference amplitude.

When an orca's call or an approaching sport fishing boat's motor noise increases in pitch, the frequency of the sound is increasing. Frequency (f) is the rate of the vibration of the wave particles, and is measured in cycles/second or Hertz (Hz). Thus, you can get a high amplitude, high frequency orca call (loud and high pitched), or a low amplitude, low frequency orca call (soft and low pitched), etc.

The wavelength of a wave is the distance a wave travels in one cycle of vibration. Wavelength and frequency are related by the sound speed of the medium. The wavelength (λ) of a sound can be calculated by:

$$\lambda = \frac{c}{f}$$

The speed of a sound wave (c) is the rate at which vibrations propagate through the water. Also, this equation shows that frequency and wavelength are inversely related, with high frequencies having short wavelengths and low frequencies having long wavelengths.

An important concept when discussing properties of sound is that of acoustic impedance. The acoustic impedance is the property of the medium that determines the ease with which a sound can be propagated. Acoustic impedance is given the relation ρc, where ρ is the density of the propagating medium, and c is the speed of sound. Because the speed of sound in water is 5 times that of air, and the density of water is roughly 1000 times greater than air, the acoustic impedance of water is much greater than that of air.

When an orca hears or receives a sound pressure pulse, it is the pressure of this sound wave to which the hair cells in the orca's ear responds. Pressure is defined as force per unit area, and is measured in micropascals (μPa). One Pascal is the pressure from the force of one Newton over an area of one square meter. The pressure $p(t)$ that is exerted on an area is proportional to the vibrating fluid particle's velocity and acoustic impedance:

$$p(t) = \rho c v$$

where v is the particle velocity.

A sound's acoustic intensity (I), is the amount of energy passing through a known area in the direction of propagation, and is measured in W/m^2. Intensity is equal to the sound pressure (p) multiplied by the volume velocity (v): $I = pv$. This can also be written as:

$$I = \frac{p^2}{\rho c}$$

since the volume velocity depends on the pressure, and inversely on the acoustic impedance.

Intensity can also be measured in decibels. Decibels are a relative measure, while W/m^2 are an absolute measure of intensity. In order to measure W/m^2, the researcher would first need to generate a known signal level at a known distance from the receiver. Since this is often difficult or impossible, decibels are more commonly used. With decibels, one can only compare signals, as in saying signal ‘a’ is 10 dB louder than signal ‘b’. The intensity level, or relative amplitude, of a sound, measured in decibels, is:

$$Intensity\ level\ (dB) = 10\ log_{10}(\frac{I}{I_R})$$

where I_R is the intensity of the reference sound, and I is the intensity of the sound to be characterized. Since sound intensity is proportional to pressure squared, this equation can be written as:

$$Intensity\ level\ (dB) = 20\ log_{10}(\frac{P}{P_R})$$

As a sound wave travels from point A to point B it diminishes in amplitude or intensity as it spreads. This is due to transmission loss. There are many reasons for such losses. As a sound propagates out from a source, there is a drop in sound intensity due to *spreading loss*. Spreading loss occurs because the sound intensity at a receiver varies inversely with the square of the distance from the source. In addition to spreading loss, there is also loss due to *absorption* by the medium. Each collision between the molecules results in some loss of energy to heat. Absorption may also occur when sound comes into contact with soft sediments, commonly characteristic of the sea floor. *Reflection* or *Scattering loss* is due to loss of sound energy when the sound encounters an object or another medium with a different acoustic impedance than the medium. Sound energy loss caused by absorption or scattering is directly proportional to the range the sound travels. *Refraction* occurs when sound rays are bent due to sound speed changes along the sound path, usually caused by temperature changes. When refraction causes many sound waves to converge, this creates areas of higher sound levels. Refraction can also cause a divergence of sound waves, which creates an area of low sound levels, called a shadow zone.

3.1.1 The Sonar Equation

It is useful to think of bioacoustics in terms of the "source-path-receiver" model [*Richardson* et al., 1995]. In this model there are: 1. a source of sound which has specific characteristics 2. changes in sound characteristics as sound travels away form the source and 3. a receiver with certain detection abilities. Consider a family group of orcas that are independently foraging along a rocky coastline and are fairly spread out in distance from each other. One orca gives a specific discrete call, and the other orcas, after receiving this call, answer back with the same call. In this case, the orca that is giving the call is the source, and the intensity of the call given is the source level (SL). Source level can be defined as the pressure level measured at a standard reference distance from a point source radiating the same amount of sound as the actual source being measured [*Ross*, 1976]. As the sound travels through the medium there will be factors that affect the sound. One needs to take into consideration transmission loss (TL), and ambient noise levels (NL). When the call reaches a second orca, the receiver, the signal to noise ratio (SNR), sound intensity level (SIL), and detection threshold (DT) are important. Also important are the animal's hearing sensitivity, its response to different frequencies, and to different types and levels of sounds. This will be discussed in more detail in future sections. A simple equation for this sound propogation could be:

$$SIL = SL - TL$$

This is known to acousticians to be one form of the sonar equation. The sonar equation is well explained by *Urick* [1983]. The sonar equation ideally will combine all the characteristics of the sonar system, the sound transmission, and scattering loss.

3.1.2 Sound Analysis

A complex wave, such as an orca call, consists of many different longitudinal, sinusoidal waves which travel together through the same space. When this happens, a displacement occurs that is the sum of all the displacements caused by the individual sinusoidal waves. In other words, the final wave amplitude that one can detect is the sum of all of the individual sinusoidal wave amplitudes. The fact that the sinusoidal waves add to produce the final wave was used by Fourier, whose theorem states that a soundwave may be represented as the sum of a series of sine and cosine waves. Thus, the pressure waveform at any time t can be found by summing the values of each of the component sine or cosine waves at that time t. The pressure P(t) of a complex periodic waveform at time t equals the sum of all the sinusoidal waves, each of which has a specific amplitude, frequency, and relative phase. Since each animal creates and responds to sounds of different frequencies, being able to convert a waveform of the signal to a spectrogram is very useful when studying bioacoustics. The Fourier transform is thoroughly explained in *Bracewell* [1978].

Any acoustic signal can be graphically or mathematically described in either a time-domain form, or a frequency-domain form. In the time domain, the amplitude of a signal is represented as a function of time. When digitizing the whale calls used in this study, the waveforms produced were in the time-domain. In the frequency domain, the amplitude of a signal is represented as a function of frequency. Most animal vocalizations, like the orca call, are quite complex, and to best describe these signals quantitatively, the whole signal must be broken up into segments, with a Fourier transform performed on each segment. The Fourier transform is a mathematical function that converts the time domain form of a signal (the waveform) to the frequency domain form, or spectrum. In practice, individual points along the signal are sampled or digitized, and a discrete Fourier transform (DFT) is performed on each one. The input to the DFT are the amplitude values of the signal, and the output is a sequence of values that show the amplitudes and phases of different frequencies.

An individual spectrum shows no information about time changes in frequency. In order to see time changes in frequency, as well as amplitude at each frequency at a particular time, a spectrogram is made. Spectrograms are made by a procedure called the short-time Fourier transform (STFT). To perform a STFT, the entire original signal is divided into successive short time intervals or frames that overlap each other in time. A DFT is performed on each frame, and this generates a series of spectra (one for each frame), that are plotted side by side to make a spectrogram. In a spectrum, frames with sharp edges cause ripples or side-lobes in the frequency, which can be reduced by multiplying the frame by a smooth window function. The window function used in this study is the Hanning window.

3.2 Noise

Orcinus orca rely on acoustic methods for communication, navigation and orientation, and maintaining social structure. One factor that may limit their acoustic system's effectiveness is noise in the medium. One way noise can be thought of is as any unwanted sound that can mask, whether partially or completely, other sounds of interest, and may even interfere with the functioning of the listener's auditory system. Types of underwater noise include natural sources of noise and man made noise. Both of these contribute to the ambient noise levels of the sea. *Urick* [1983] defines ambient noise as total background noise observed with a nondirectional hydrophone that is not due to the hydrophone. Recently, the ocean's rising ambient noise levels have been a source of concern, especially with respect to how it might affect marine organisms. In this thesis, I classified anthropogenic noise as identifiable nearby noise sources (in this case individual vessels) over and above the background ambient noise. Extremely distant ship traffic does affect the overall ambient noise level of the sea, and is the dominant source of noise around 100 Hz. However, this noise is different from the anthropogenic noise in this study, in that the ships are so distant that one cannot make out individual ship noise.

There are many sources of noise in the sea. Environmental sources include biological noise, such as snapping shrimp, noise from precipitation, wind and wave noise, current noise, ice noise, seismic noise, and thermal noise. Human-made noise contributes greatly to rising ambient underwater noise levels. Unfortunately, noise is an unavoidable by-product of machines. With each work producing force, there is always some small vibrations which radiate as sound. When a vessel moves through water, turbulent motions are created which generate sound. Examples of human-made sources of noise in the sea include aircraft, icebreaking, seismic surveys, sonar, explosions, drilling, dredging, and vessel noise. Much of this noise comes from activities such as marine construction, oil and gas production, shipping, the fishing industry, transportation, geophysical surveys, and even land-based activities such as logging. This study is concerned with vessel noise, most specifically that from shipping, tourism vessels, sport boats and fishing boats, since these are the vessels most likely found near pods of orcas in the study area.

Vessel traffic in the ocean has been steadily increasing each year. As a result, underwater ambient noise levels have also been increasing. Vessel noise differs greatly due to differences in vessel design, size, and speed of the motor. All of these variables will contribute to a change in the frequency range and levels of noise. The major source of noise from all vessels is propeller cavitation (Ross 1976). Cavitation is defined as the forming of visible bubbles in a liquid caused by reduction of local static pressure. A second major source of noise is propeller singing. *Richardson* et al. [1995] defines propeller singing as when vortex shedding frequencies intensify a resonant vibrational frequency in a propeller blade. Other sources of noise from vessels may include rotation shafts, gear teeth, fluid flow turbulence, mechanical friction, pumps, and generators [*Richardson* et al., 1995]. These sources of noise originate inside the vessel and radiate out into the water.

Responses by cetaceans have been found to vary with boat size. *Baker* et al. [1982] found that humpback whales responded differently to different size vessels. The presence of

Vessel Description	Vessel Length (m)	Frequency (Hz)	Source Level (dB re μPa @ 1m)
Outboard Zodiac[a]	5	6300	152
Outboard drive[a]	5	630	156
Fishing boat[b]	12	250-1000	151
Tug Pulling Empty Barge[c]	25	1000	170
Twin Diesel[a]	34	100	158
Super Tanker[d]	340	6.8	190

[a] Malme et al (1989)
[c] Miles et al (1987)
[b] Greene (1985)
[d] Ross (1976)

Table 3.1: Fundamental Frequency and Estimated Source Levels of Various Vessels. A range of various vessel sizes are listed with the fundamental frequency and source level of noise generated by each vessel. This table is taken from *Richardson* et al. [1995].

large ships resulted in significant increases in the whales taking short pauses and significant increases in dive times. Large ships were also significantly correlated with faster whale speed. *Stewart* et al. [1982] noted that beluga whales had a stronger reaction to outboard powered vessels than they did to boats with diesel engines. Reactions from these whales include avoidance by diving, swimming away, or cessation of behaviors such as feeding, resting, or social interactions. Smaller vessels have smaller propellers with high rotation rates, thus the cavitation noise from these boats will be at higher frequencies than that from a larger vessel. Larger vessels tend to have lower frequencies than smaller vessels. In the sea, underwater noise at lower frequencies, from 20 to 300 Hz, tends to be from shipping [*Richardson* et al., 1995]. Larger vessels also tend to be louder. *Young and Mille* [1960] found that an 18 horsepower motor produced 4 dB more sound than a 7.5 horsepower motor. That larger vessels are louder and have lower frequencies is due to their greater power, larger size, and slower turning engines and propellers [*Richardson* et al., 1995]. Table 3.1 shows some differences in frequency and source level for various vessels. Speed of the vessel also affects the noise it makes. Both frequency and intensity will increase with increasing vessel speed [*Richardson* et al., 1995]. *Young and Mille* [1960] found that the main effect of increasing the speed by just one knot was to increase the frequency by an average of 5 Hz. They also noted that machinery noise tended to vary with speed, another cause for noise variation.

Coastal areas probably have some of the largest amounts of vessel traffic, and thus they also tend to have a great deal of noise. In any one coastal area there may be recreational boats, research vessels, tour vessels, sport fishing as well as commercial fishing boats, ferries, and ships. In nearby deeper waters there may be ships, barges, commercial vessels and huge tankers adding to the overall noise levels. Even though it is not possible to eliminate all noise from a mechanical system, there are measures that can be taken to reduce as much noise as possible. Noise is generated in three steps: generation of a vibratory motion, transmission of this vibration to a radiating surface, and radiation of sound into the medium [*Ross*, 1976]. To reduce noise, one must work on reducing each of the three parts mentioned above. This has been done to a great extent, but although boat motors are quieter now than in the past, there are still noise control measures that could be used to decrease the noise output of boats. Some noise reducing suggestions from *Young and Mille* [1960] include vibration-isolated suspension, a rubber mounted hood, an air intake silencer, and a modified underwater exhaust.

3.2.1 Signal to Noise Ratio

One important aspect of how noise levels affect marine mammals is the signal to noise ratio (SNR). The SNR is calculated as the difference between the signal level and the noise level (in dB). For example, if one whale were to emit a call, the SNR at the whale receiving the signal would be: $SNR = SL - LN = LS - TL - LN$, where SL is the signal level in the water at the receiving whale, LN is the background noise level, LS is the source level of the call (in dB relative to 1 μPa), and TL is the transmission loss of the signal as it travels through the water. The SNR indicates whether or not a particular acoustic signal can be detected. A SNR greater than 0 dB indicates that the signal is detectable over background noise, while a SNR less than 0 dB would mean the signal is undetectable.

3.2.2 Critical Ratio

When considering the potential effects for acoustic interference from anthropogenic noise on whales, one needs to understand the critical ratio. The critical ratio (CR) is defined as the number of decibels a signal with a pure tone must surpass the background noise in order to be heard. The critical ratio is important in figuring out the range in which noise will interfere with an animal's hearing sensitivity. Critical ratio information helps to determine the frequencies and levels at each frequency that are most likely to be masked. Critical ratios differ from SNRs in that CRs relate the level of a signal to the spectrum level of background noise at frequencies near that of the signal. A CR of 20 dB at 10 kHz means that a signal of 10 kHz must exceed noise levels near this frequency by 20 dB in order to

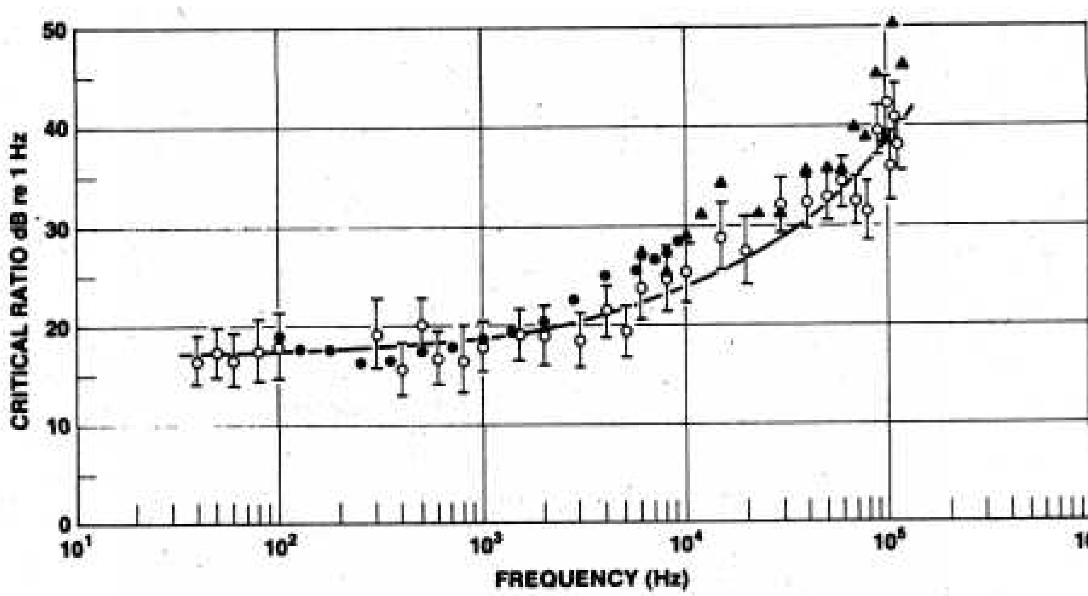

Figure 3.1: Example of Critical Ratio. An example of critical ratio data for a beluga whale listening underwater. This figure is taken from *Johnson* et al. [1989]

be heard. *Bain and Dahlheim* [1994] found that critical ratios for a killer whale range from 20 dB at 10 kHz to 40 dB at 80 kHz. Since orca vocalizations are high in frequency, it is interesting to note that CRs tend to increase with increasing frequency. This increase means that at higher frequencies, the whale's ability to hear that frequency over the background noise deteriorates. This increase in critical ratio with frequency is typical of terrestrial mammal hearing. Figure 3.1 shows an example of the critical ratios for different frequencies for a beluga whale. At higher frequencies, the level of the call must exceed the background noise level by a greater amount in order to be heard by a receiving cetacean.

3.2.3 Effects of Noise

Our present knowledge of the effects of noise on marine mammals is limited. Most studies have been on terrestrial animals, and many of the studies done on marine mammals have been on those animals in captivity, which may not give the same results as a study on the noise effects on a free-ranging animal. The acoustic sense of marine mammals is probably their most important sensory system, providing information on a variety of functions relative to navigation, predation, and intraspecies communication in the obscure waters where they live. Human-made noise, depending on its intensity, frequency range, and duration, can have many possible effects on marine mammals, and this section provides information on some of these effects.

Masking

When an orca is listening for one of its pod member's calls in the presence of background noise, the threshold for hearing a certain call depends upon the intensity of the noise. The noise, as it increases, will diminish the ability of the orca to detect the call. This is called masking. The orca uses modulated broad-band sounds, perhaps because a pure tone can be more easily masked than a broad-band sound [*Dubrovskiy*, 1990]. Even in a natural noise environment, the noise levels can be quite loud and prevalent. This is one advantage of orca calls being so rich and complicated in structure.

An orca call, or any acoustic signal, is most severely masked if the noise is similar in structure to that of the call, or if the noise source is near the signal source. So, a boat near to a group of orcas will have more effect than a distant boat. This is because sound energy is absorbed and scattered as it propagates through the water. *Schevill and Watkins* [1966] proved in a study that the high frequency vocalizations given by orcas are highly directional, and propagate in the forward direction. A study by *Bain and Dahlheim* [1994] showed that if there are low levels of noise, and the orca vocalizations are high enough in energy, then boat noise has little or no masking effect. However, they did find that a vessel directly in front of a calling orca was more likely to mask or partially mask a call. There are other factors to take into consideration when looking at vessel noise effects on orcas. For example, unlike the high frequency components of orca calls which are extremely directional, the low frequency components of the calls are omnidirectional [*Schevill and Watkins*, 1966]. *Bain and Dahlheim* [1994] found that vessel noise would impair an orca's detection of low frequency signals up to 20 kHz. This masking may affect communication in groups of orcas swimming side by side, which family groups of orcas often do. The possible effects of this disruption are unknown. They suggest that if there are high enough levels of noise, then the more omnidirectional low frequency calls would definitely be masked or partially masked by the noise. Apparently, even the higher frequency calls could possibly be affected by vessel noise. From experiments with human subjects it has been found that low frequency tones are more effective in masking high frequency tones than high frequencies are in masking low frequencies [*Wegel and Lane*, 1924; *Munson and Gardner*, 1950; *Egan and Hake*, 1950]. *Bain* et al. [1993] found that very loud, low frequency noise reduces the orca's ability to detect even those calls that are at much higher frequencies than the noise.

More studies are needed on the effects of masking by high level vessel noise, keeping in mind vessel noise levels at different distances, and the location of the vessel relative to the signal and to the receiving orca. Masking by anthropogenic noise could result in decreased foraging, navigational, and communication capabilities in whales.

Physiological and Psychological Effects

Intense sound can affect various bodily functions, and can even kill an animal if the sound levels are high enough, and animal is close enough to the source. It can affect and harm the auditory system, and it can also affect cardiovascular and circulatory systems, sleep, endocrine levels, reproduction, susceptibility to infection, metabolic functions, and neurological functions. If an animal is exposed to repeated high levels of sound, hearing loss, whether temporary or permanent, can result [*Kryter*, 1985]. Although only few studies on hearing loss in marine mammals have been made, whales that were killed by underwater explosions were found to have severe auditory damage [*Ketten* et al., 1993]. A study by *Kastak* et al. [1998] examined temporary hearing loss in pinnipeds exposed to moderate duration and intensity noise. Immediately after exposure to 20 minutes of noise, with frequencies ranging from 100 Hz to 2 kHz, and levels at 60-75 dB, the animals showed 4.6 to 4.9 dB hearing threshold shifts.

Besides damage to hearing, sound exposure has been found to be harmful in causing stress to an animal. Marine mammals have been seen to remain in an area even though there is much human-made noise [*Richardson* et al., 1995]. These animals seem to tolerate the noise, and carry on with normal activities. They may do so because there are no other areas that meet their requirements [*Brodie*, 1981], and unfortunately, the noise may be causing these animals stress. Stress is defined as any physiological response of an animal to some external stimuli that helps the animal to cope with a dangerous situation, with repeated activation of stress related mechanisms possibly leading to harmful physiological effects [*Seyle*, 1973]. *Jensen and Rasmussen* [1970] found that noise at 800 Hz and 120-123 dB causes emotional stress and increased susceptibility to infection in mice. *Arguelles* et al. [1970] confirmed that endocrine disturbances can be caused by sound stimulation. Noise exposure to animals has also been found to increase blood cholesterol levels [*Friedman* et al., 1967], constrict blood vessels [*Rosen*, 1970], increase blood pressure [*Rosencrans* et al., 1966], and decrease uterine blood flow [*Franklin and Brent*, 1964; *Senger* et al., 1967]. The significance of such responses to noise are probably negligible if the disturbance does not occur often.

The examples above were all from laboratory experiments, whereas in the wild, an animal exposed to extremely intense noise can usually leave the area. Unfortunately for the whales in this study, the coastal region where they live has high levels of human activity, and it is often not possible for marine life to escape the resulting auditory interference.

Behavioral Effects

There have been many documented events of disturbance reactions of marine mammals due to ships and boats. Investigating these behavioral reactions to loud sounds and the effects on marine mammals may help to define zones of impact [*Richardson* et al., 1995]. Reactions to noise exposure can range from an extremely subtle reaction, such as a hauled out pinniped lifting it's head, to more obvious reactions such as short interruptions of normal activities to short or long-term displacement from an area. A single noise exposure event is not likely to have long term effects, unless the incident has extremely high exposure levels that might result in acoustic trauma or damage. But there can be consequences from a single noise event such as startle responses or avoidance that may interrupt behavior, which could, for example, cause mothers and offspring to be separated. A single event also may cause disruption in communication, navigation, and foraging. If the animals are repeatedly disturbed, this could mean severe energetic consequences for them.

Behavioral disturbances due to vessel noise may include social disruptions, feeding disruptions, changes in respiration, swim path, surfacing or diving. Studies on responses to vessel noise have shown both disturbance and non-disturbance behavior. Often the reaction depended strongly on distance [*Fay* et al., 1984], or on how often the animals were hunted [*Malme* et al., 1989]. Reactions in pinnipeds include waking up, head raising, and entering the water. If adults enter or stampede into the water, this could lead to increased predation, injury, and abandonment of juveniles [*Fay* et al., 1984]. Disturbances in vocal activity is also a social disruption, and has been observed in several marine mammal studies [*Norris*, 1994; *Lesage* et al., 1993; *Dahlheim*, 1987; *Dahlheim* et al., 1984]. One study on behavioral effects examined the vocal activity of harp seals in the Gulf of St. Lawrence, Canada [*Terhune* et al., 1979]. In this study, seal vocalizations decreased upon the arrival of a vessel. The seals either became less vocal at the arrival of a boat, or they left the area altogether. Many studies on cetaceans show obvious avoidance reactions or change in activity to vessels [*Reeves*, 1992; *Kruse*, 1991; *Blane*, 1990; *Brodie*, 1981; *Lockyer*, 1977]. For example, *Williams* [1999] examined the effects of boat traffic on resident killer whale behavior in Johnstone Strait, and found that the whales tended to swim in a less predictable path when boat traffic was nearby. Female orcas would respond by swimming faster and more erratically. Males maintained their speed and chose a smooth, yet less direct path. Another serious effect that may be caused by repeated noise exposure is long-term displacement from an area. The consequences of these short and long-term disruptions to marine mammals are unknown. Most of these studies involve a relatively small sample of marine mammals. Since an individual animal's reactions may vary, it is difficult to make predictions for entire populations.

3.2.4 Noise Reducing Adaptions

There are several ways in which a marine mammal may reduce the effects of masking by noise. Three adaptions odontocetes use are frequency discrimination, intensity discrimination, and directional hearing. These discrimination abilities are very important for an odontocete to recognize various types of calls or in recognizing individual whales amidst background noise.

Frequency discrimination is one way in which an odontocete may increase the chances of detecting a signal above noise. The odontocete's brain is well adapted to receive specific sound types. For example, *Bullock* et al. [1968] found that frequency modulated (FM) tones were more likely to be recognized by the odontocete brain than constant frequency tones. Thus, the orca is adapted to better receive the kinds of frequency modulated discrete calls that it produces. Being able to distinguish different frequencies is important in detecting acoustic signals. Underwater noise, such as boat noise, can impair the ability of an orca to detect a tone. The tone is most masked by noise that is at the same and nearby frequencies. An orca, by modulating the frequencies of a specific call, can reduce the effects of masking on the call due to the presence of background noise, whether man-made or natural. Perhaps this is why orcas have calls with changing frequencies and many harmonics. Frequency discrimination is also essential to an orca in distinguishing between different types of calls.

Intensity discrimination is a second method odontocetes use to detect sound signals in the presence of noise. Several studies have shown that odontocetes may be able to discriminate between signals that differ by as little as 1 decibel [*Bullock* et al., 1968; *Johnson*, 1967].

Odontocete hearing is directional. *Norris* et al. [1961] observed that blindfolded bottlenose dolphins (*Tursiops truncatus*) can not detect targets below their jaws and at elevation angles greater than 90 degrees above the rostrum. Directional hearing is a third method in which odontocetes may reduce the effects of noise on their acoustical communication. This ability to localize a sound source can help when the the noise and the sound signal are coming from different directions. In odontocetes with high frequency hearing, there is evidence that masking depends greatly on the direction of arrival of the sound signal and that of the masking noise [*Au and Moore*, 1983; *Bain* et al., 1993; *Bain and Dahlheim*, 1994].

Chapter 4

Experiment Description and Analysis Methods

4.1 The Study Area

British Columbia's inside passage consists of rugged, rocky beaches, fjord cut inlets, and temperate rainforests. The study area includes west Johnstone Strait, Blackney Pass, and Blackfish Sound just northwest of Vancouver Island. Johnstone Strait borders the northeast coast of Vancouver Island, Blackney Pass includes the waters located between West Cracroft Island and Hanson Island, and Blackfish Sound is located just north of Hanson Island (See Figure 4.1).

The study area is a beautiful and bountiful place, and is used and visited by many people, with increasing numbers each year. There are various sources of human-made

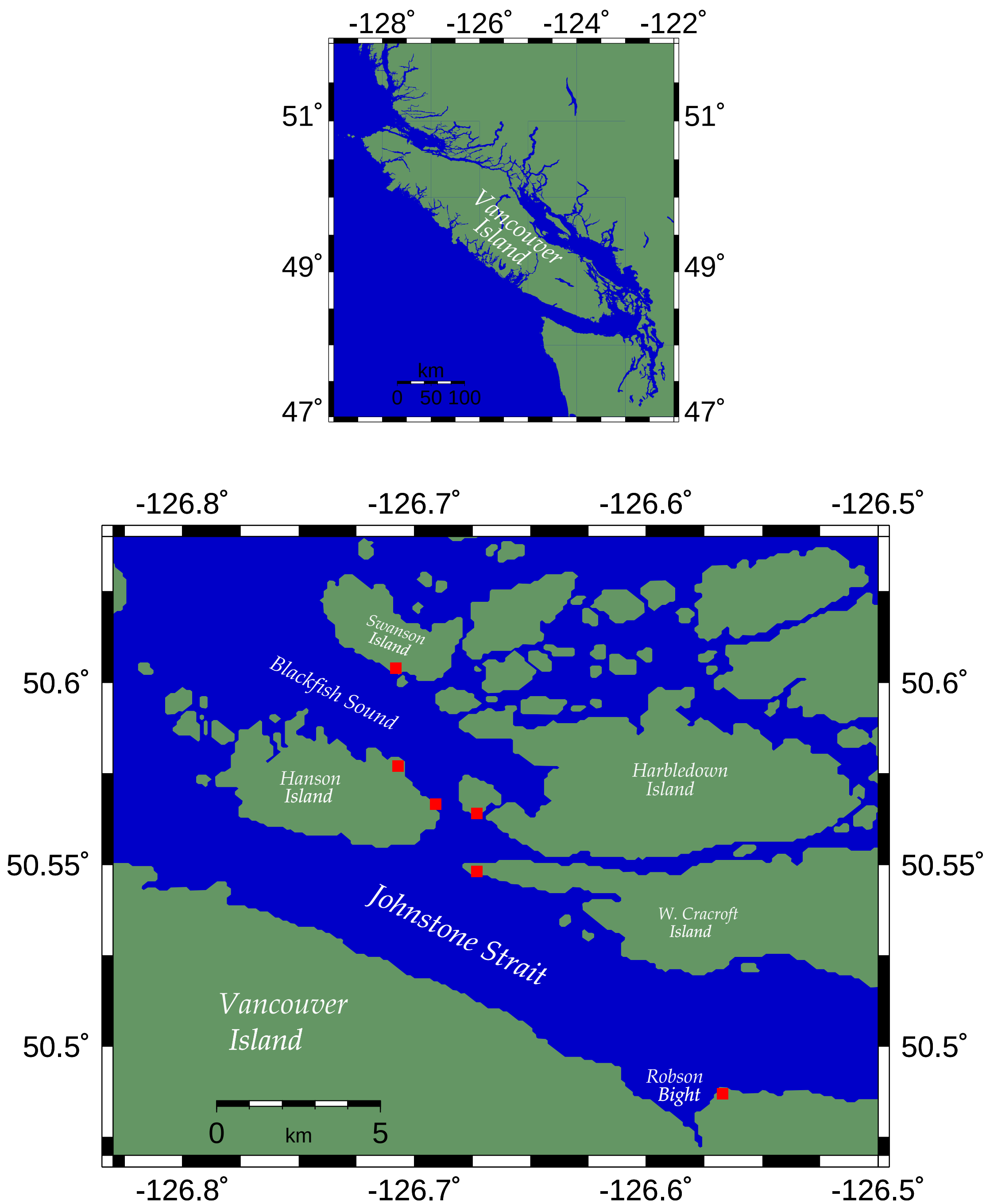

Figure 4.1: Map of Study Area. Map of the study area showing the location of the hydrophones as red boxes. The top panel shows Vancouver Island, which is located in British Columbia. The study area is shown in the bottom panel, with the exact latitude and longitude. The study area is located just off of north Vancouver Island, and includes Johnstone Strait and Blackfish Sound.

Figure 4.2: Orca and Nearby Vessel Traffic. This photo, taken in the study area, shows the common sight of killer whales and nearby whale-watching vessels.

sound in the study area that could possibly affect orca vocal behavior. The area supports logging and commercial fishing, and the waters are shared by sport and commercial fishing vessels, kayakers, ferries, barges, researchers and tour boats. Whales and people often come into close proximity, and it is not uncommon to see a pod of orcas swimming extremely close to groups of boats filled with curious people (See Figure 4.2). Many people come to this area specifically to see the killer whales, and this has resulted in many whale-watching businesses. In order to keep the impact of all this activity on these animals at a minimum, vessels are advised to approach the whales carefully from the side, not to approach any closer than 100 m, and to avoid crowding the whales near the shore or other boats. It is also advised to limit whale watching time to less than 30 minutes when within 100-200 m.

Besides human-made noise, many natural sources of noise are also found throughout the study area. The major sources of natural ambient noise are probably wind noise, precipitation noise, and noise from tides and currents. Noise due to wind speed and rain would commonly affect the overall noise levels of the recordings in this study. Other sources of noise include those of biological origin. Snapping shrimp are occasionally heard, usually in shallow coastal waters. These shrimp are known for their intense broad-band clicks which sound much like static or loud crackling. Besides the orca vocalizations that this study addresses, there are also occasional whistles from dolphins in the area.

Background noise containing both natural and human-made noise typically ranged from 1 Hz to 4 kHz, with the highest levels of boat noise around 200-500 Hz. Figure 4.3 shows examples of some of the different background noise levels seen throughout the study area. Each spectrogram in this figure shows a different recording of vessel noise. Differences in frequency and amplitude may be due to the vessel type, motor type, speed of the vessel, or the distance of the vessel to the hydrophone.

4.2 Equipment

All acoustical data came from Orcalab, located on Hanson Island. Orcalab, run by Paul Spong and Helena Symmonds, is a land-based whale research station that does long-term studies of the area's orca populations and evaluates human impacts on them. Orcalab's philosophy is that it is possible to study wildlife in a non-intrusive way, and it does so with a hydrophone network that extends among five different islands: Swanson Island, Hanson Island, Parson Island, W. Cracroft Island, and Vancouver Island (See Figure 4.1). The Orcalab hydrophone network consists of 6 remote stations each of which contains a hydrophone connected by cable to a radio transmitter. The Orcalab hydrophones mostly consist of hy-

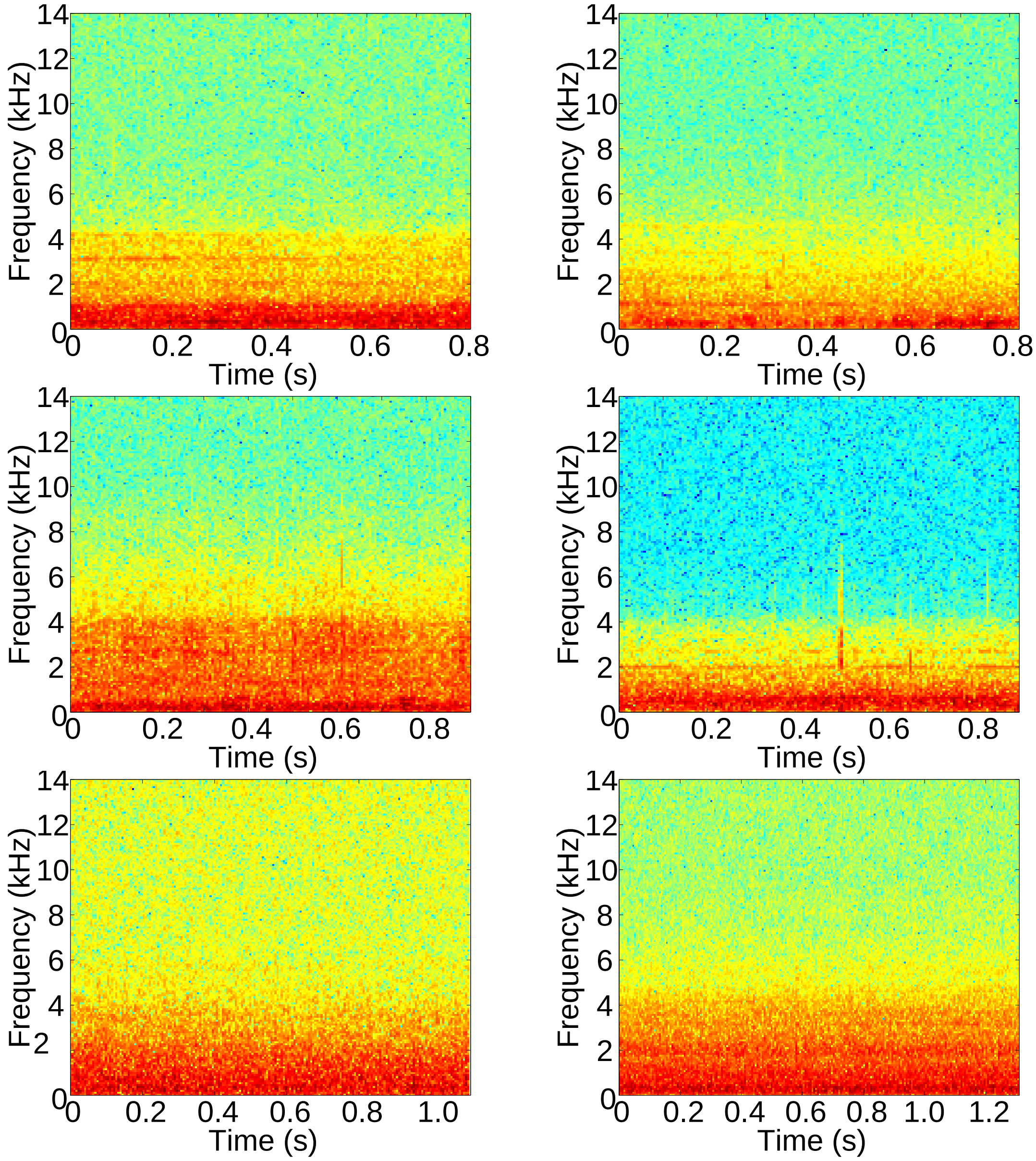

Figure 4.3: Spectrograms of Noise. Each panel shows a spectrogram from a different recording of boat noise. Different vessel types, motor types, and motor speeds will show differences in frequency range and amplitude in the spectrograms. Note that in the middle two panels there are some spikes in the noise. These could result from the hydrophone bumping or scratching along the bottom.

drophones from old military sonobuoys. The frequency response of the hydrophones is fairly flat (+/- 3 dB) from 100-9000 Hz. Between 9000-20000 Hz the response is more variable, and the response of the hydrophone then falls off beyond 20 kHz. The hydrophones are each at a depth of 20 m, and the whole network covers a range of about 15 km. The transmitter broadcasts a continuous signal that is monitored on a receiver at the base laboratory. Vocal whales are recorded by volunteers at Orcalab with Sony TC-D5M recorders.

4.3 Analysis of Recordings

The hydrophones used in this study are permanent stationary hydrophones deployed from shore and linked to Orcalab by VHF radio. All acoustic recordings were first copied from analog cassette tapes to analog cassette tapes from the Orcalab data set. From the Orcalab recordings, recordings from the killer whale subpod A36, which belongs to the A1 pod, were chosen since this resident pod is known to frequent the area regularly. A total of 61 tapes were copied from times when the A36 subpod was alone in the study area. These tapes covered recordings made during the summers of 1993, 1994, 1996, 1997, and 1998. Initially, tape times when whale vocalizations were present in the recordings were noted, as well as general information on ambient noise levels and human-made noise. Recordings were eliminated from analysis if they included no whale vocalizations, or extremely high levels of boat noise. In this latter case, when boat noise levels were exceedingly high, no discrete calls could be successfully analyzed over the noise. Recordings of extremely faint (or distant) discrete calls or overlapping calls also were considered unfit and were not used in the analysis. Recordings of calls that were sufficiently loud and distinct were considered ideal. From these a quality spectrogram could be made and analyzed. Most of the recordings contained both the presence of whales and boat noise; in very few recordings were there discrete calls alone with no boat noise present. Many of the calls classified as having no noise do actually have some noise. This noise was usually from water noise, electrical noise, or occasionally from very distant shipping noise. Only those calls with recognizable, loud individual boat noise nearby were classified as calls with noise.

Selected calls were digitized using Sound Blaster AWE64 Gold WaveStudio from cassette tapes at a sampling rate of 44.1 kHz. Call spectral variables were measured using Matlab and the Matlab Signal Processing Toolbox. In order to create spectrograms of the data, the Matlab command 'specgram' was used. Matlab then takes a Fourier transform of all data points from the digitized waveform of the data. The sampling rate was set at 44.1 kHz, meaning Matlab takes every 44,100 samples to be equal to one second in time. To look at how the signal parameters change in time, it is practical to work with short frames of the signal or 'windows'. For this study, the window length was set at 256 data points, so every time slice is made up of 256 data points. Matlab takes the Fourier transform of the 256 data points, and that is plotted as the first time segment. The next 256 data points is plotted as the next time segment, etc. Thus, Matlab builds up the spectrogram image, as described in section 3.1.2. Matlab by default uses overlapping Hanning windows. A Hanning window is a certain length signal used to select a desired part of the original signal by a simple multiplication process. The Hanning window is defined as:

$$w(k) = 0.5[1 - cos(2\pi k/n + 1)]$$

where k goes from 1 to n, and n is the length of the signal (same as the duration of the window). *Yu* [1999] and *Szuberla* [1997] give a detailed description of the Hanning window. Also, it is important to note that in order for Matlab to assign decibel levels to different intensities in the spectrogram, it takes 20 times the base log of the absolute value of the Fourier components. Recall that $Intensity\ level\ (dB) = 20\ log_{10}(\frac{P}{P_R})$. Thus, Matlab is assigning decibel levels referenced to 1 volt. The end results are spectrograms created for each call analyzed in this study. From the spectrograms of each call, time and frequency measurements could be made using the mouse and cursor, as well as certain commands in Matlab. Measured values were then put into Excel spreadsheets where they could be analyzed statistically. Statistical analysis was done using STATISTICA.

The N1, N4, N5, and N7 call types were chosen as those to analyze by comparing different spectral characteristics in the presence of boat noise and in acoustically quiet conditions. These call types were used due to the greater number of suitable calls. In order for a call to be suitable, it must be sufficiently loud, it must not have another call overlap it, and the boat noise must not be so loud that it drowns out the call. Figure 4.4 shows spectrograms of these four calls. A table of each individual call that was analyzed and compared is shown in Table A.1. Three spectral characteristics for the N5 call, and four call characteristics for the N1, N4, and N7 calls were measured. Because there were only a sufficient sample number of the N4 and N5 calls, in the end they were the only calls which the spectral characteristics

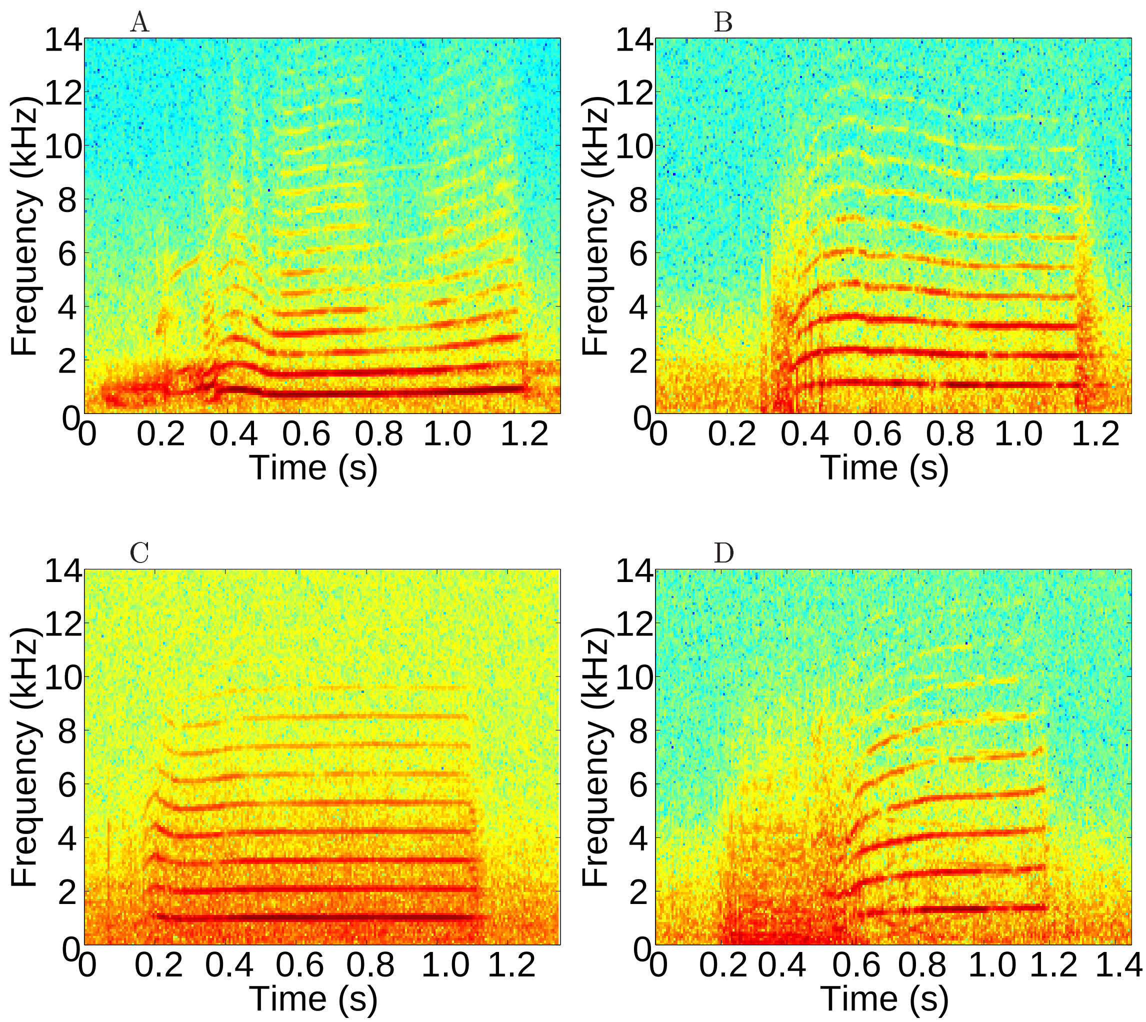

Figure 4.4: Spectrograms showing the N1 (A), N4 (B), N5 (C), and N7 (D) calls of subpod A36.

could be statistically compared with and without boat noise. The spectral characteristics measured for the N4 call include the average frequency of the first harmonic, the number of harmonics, the total duration of the call, and the duration of the frequency peak of the call. Figure 4.6 shows examples of spectrograms of the N4 call with and without boat noise. The average frequency of the first harmonic was defined as the mean of the frequencies of that harmonic. For consistency, the first harmonic was chosen because it almost always had the strongest signal levels. The number of harmonics for a call was defined as the total number of harmonics visible. In the spectra, I defined a harmonic as visible if it was at least 5 dB above the background noise. At the beginning of the N4 call there is a characteristic peak in the frequency of the call (See figure 4.6). For the N4 call, the duration of the peak of the call was defined as the duration from the start of the call to the highest point in the peak. For the N5 call, average frequency of the first harmonic, duration, and number of harmonics of each call was measured. In this study, there were limitations in comparing intensities between calls. First, the Orcalab hydrophones and other equipments are not calibrated. Second, volunteers at Orcalab change the recording levels often in order to better hear the whales. The distance of the whales from the hydrophone at any time was unknown, so measurements of intensity are unreliable, and could not be compared between the different recordings. Also, intensity would depend greatly on the direction a calling whale was facing, which could not be determined in this study.

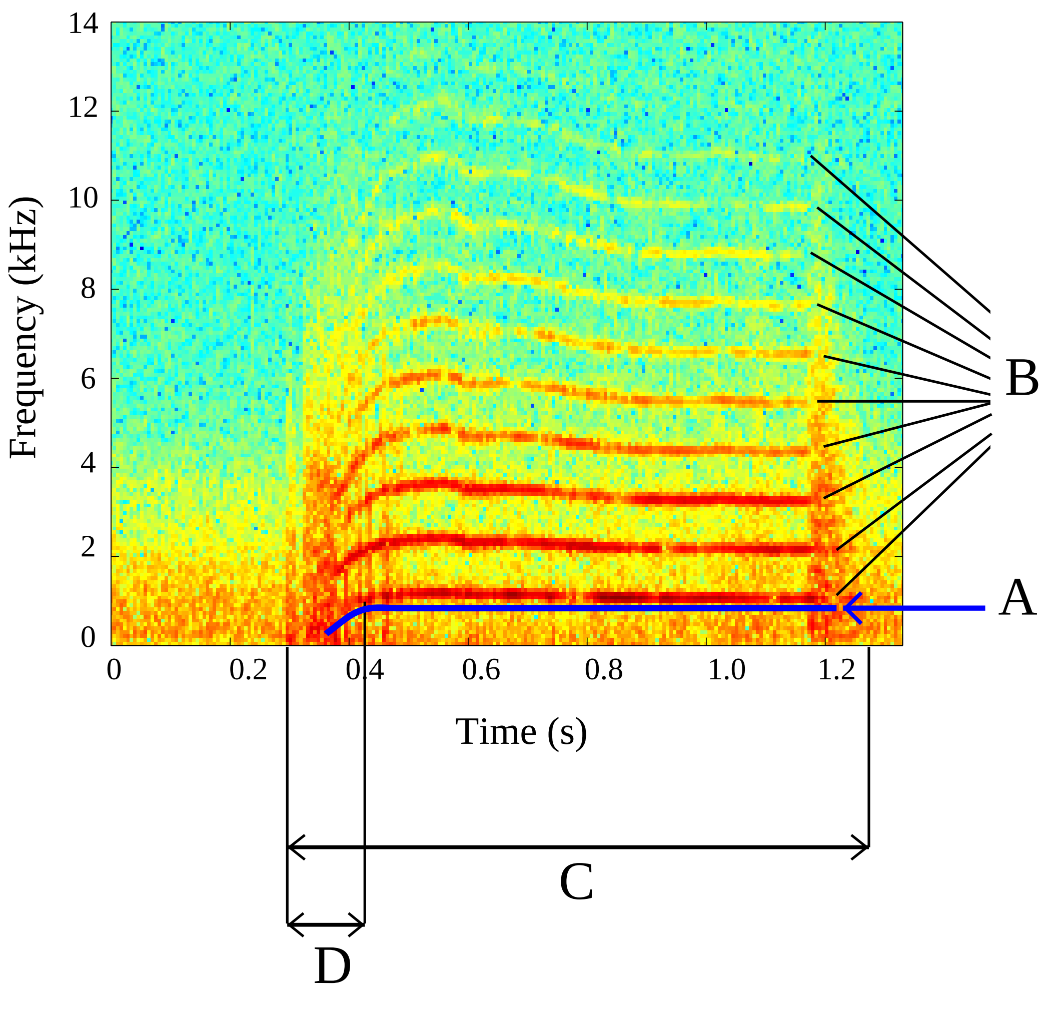

Figure 4.5: Spectral Characteristics Examined. This figure shows the spectral characteristics examined for the N4 call. The average frequency of all the frequencies that make up the first harmonic was calculated (A) for each call. The number of harmonics (B) was calculated for each call. The duration (C) of the total call length in seconds was calculated, as was the duration of the peak in frequency of the call (D).

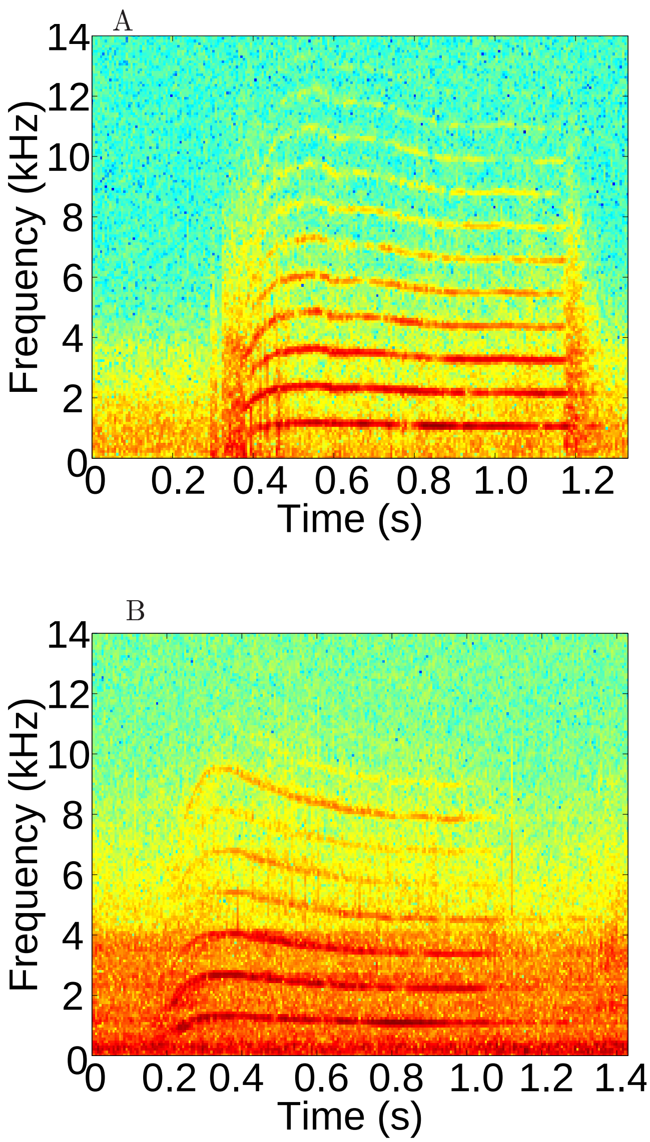

Figure 4.6: Spectrograms showing the N4 call of subpod A36 without (A) and with (B) nearby boat noise.

Statistical Analysis

Call variables were compared statistically using STATISTICA. Calls were categorized into two types: those with boat noise and those without boat noise.

Boxplots were used to examine means, and standard deviations for the different call characteristics of the N1, N4, N5, and N7 calls, either in quiet waters, or in noisy waters. Histograms were used to visually compare distributions for the N4 and N5 calls.

Because they had a sufficient sample size, only the N4 and N5 calls were then analyzed using the Mann-Whitney U test and the Kolmogorov-Smirnov test. The medians of two samples were compared using the Mann-Whitney U test. This test was used because it is a non-parametric technique that can be used for data with a small sample size or for data with unequal sample sizes, and because it is suitable for data which is not normally distributed. The Mann-Whitney U test is a powerful (or sensitive) nonparametric alternative to the t-test for independent samples. The interpretation of this test is the same as the interpretation of the results of a t-test for independent samples, except that the U test is computed based on rank sums rather than means. In some instances the Mann-Whitney U test may offer even greater power to reject the null hypothesis than the t-test [*STATISTICA*, 1994]. In this thesis, the null hypothesis is always that there is a difference in the call characteristic when compared with and without noise. The Mann-Whitney statistic is calculated as from *Zar* [1996]:

$$U = n_1 n_2 + \frac{n_1(n_1+1)}{2} - R_1$$

where n_1 and n_2 are the number of observations in samples one and two, and R_1 is the sum of the ranks of the observations in sample one. The hypothesis that the two samples come from identical populations is tested against the alternative hypothesis that the two populations have unequal averages. This is done by comparing the U statistic to the tabular U statistic. If the U statistic calculated is less than or equal to the table U statistic, then the null hypothesis is rejected and the two populations are thus found to have unequal averages.

The Kolmogorov-Smirnov two-sample analysis was used to test any differences in the general shapes of the distributions in the two samples. Differences in distribution shape could be due to differences in location, skewness, kurtosis, and so forth. The two-tailed critical value for the test statistic D is computed as in *Sokal and Rohlf* [1981]:

$$D_\alpha = K_\alpha \sqrt{\frac{n_1 + n_2}{n_1 n_2}}$$

where $K_\alpha = \sqrt{\frac{1}{2} - \ln \frac{\alpha}{2}}$, and the error level $\alpha = 0.1$. The D statistic is then compared to the tabular D statistic at that alpha level, and if it is greater than the tabular D statistic, then the two samples came from populations with different distributions. If the D statistic is significant, then the hypothesis that the two distributions are the same should be rejected.

4.4 Average Call Rates Analysis

It has been suggested by Helena Symmonds and Paul Spong of Orcalab that resident orca call rates decrease temporarily when a vessel comes within auditory range. Thus, they have observed the whales calling less or becoming more silent when vessel noise can first be heard, and then gradually the whales increased their calling rates again, perhaps while the boats were still in the area. Average call rates were examined by a comparison of the average of the number of calls per minute from recordings with and without boat noise. For each recording period, the total time of the recording, the number of each call type, and the level of boat noise was recorded (See Table A.2). From these recordings, the average call rates for individual calls were calculated by:

$$Average\ Call\ Rate = \frac{\sum(\frac{number of calls}{time period})}{N}$$

where N=the total number of recording periods where that specific call showed up. The number of recording periods where that call type was heard (N) is used in the calculation so that average call rates can be compared between different call types. This standardizing must be done because one call type may have been found in only five recording periods and another might be found in all 32 recording periods. The time period is the total time of the specific recording period, and the number of calls is the total number of the certain call type in that recording period. This average call rate was calculated for each individual call for recordings when there was no boat noise present, and again when there was boat noise. Average call rates were calculated for each call type taking into account every recording session that contained that specific call type. Average call rates were also calculated for the total calls overall.

Chapter 5

Results of the Analysis

5.1 Statistical Results from Spectral Comparison

Various characteristics of each call type were compared with and without boat noise. Medians were compared, as well as the distributions of the different spectral characteristics. The data appeared to have many different distribution shapes, so non-parametric tests were used. A significance level of 0.1 was used because of the small data set, thus choosing to possibly err on the side of saying there is an effect, or there is a difference between medians. My results fairly consistently showed no difference in comparisons of the spectral characteristics chosen, whether the whales were vocalizing in the presence of boat noise or not.

5.1.1 Average Frequency of the First Harmonic

The average frequency of the first harmonic in each call's spectrogram was calculated using Matlab. Each orca call is made up of a number of harmonics. The first harmonic was chosen because it is often the strongest harmonic. I hypothesized that perhaps in extremely loud boat noise, the average frequency of the first harmonic, and subsequently, all the harmonics of the call, might increase or decrease in order to find a niche not occupied by noise. I tested for this change in frequency by taking the average of all the frequencies along the first harmonic, from start to finish of the call. This average frequency then represented the overall frequency of the first harmonic. Then, I compared the average frequencies for call types N4 and N5 when they were and when they were not in the presence of loud boat noise. The data from these calculations can be seen in Table A.3.

N4 Call

The mean for the N4 call's average frequency without noise was 1.232 kHz ± 0.122 kHz, while the mean for the average frequency with noise was 1.196 kHz ± 0.074 kHz (See Table 5.1 and FigureB.1).

The results from the Mann-Whitney U test (See Table 5.2) show no significant difference between medians of the N4 call's average frequency with and without noise (z=1.489027, p-level=.136490). The results from the Kolmogorov-Smirnov test (See Table 5.3), however, show that there is a significant difference in the distributions of the two groups. As seen by the histograms of the two groups, the data from average frequency of the N4 call

N4 Call

Average Frequency

	n	mean (kHz)	median (kHz)	std dev
no boat noise	24	1.232	1.248	0.122
boat noise	35	1.196	1.190	0.074

Number of Harmonics

	n	mean (s)	median (s)	std dev
no boat noise	24	6.958	7.0	2.804
boat noise	36	6.085	7.0	1.686

Duration

	n	mean (s)	median (s)	std dev
no boat noise	24	1.015	0.985	0.194
boat noise	36	1.012	0.978	0.185

Peak Duration

	n	mean (s)	median (s)	std dev
no boat noise	24	0.134	0.116	0.042
boat noise	36	0.122	0.116	0.035

Table 5.1: Descriptive Statistics N4 Call. Descriptive statistics of the N4 call's average frequency of the first harmonic, the number of harmonics, the duration, and the duration of the peak of the call with and without boat noise.

without boat noise has a more rectangular, or flat, distribution, while the histogram of average frequency with noise has more of a normal distribution, with much more kurtosis, or peakedness. The frequencies from this histogram appear to peak around 1.155 kHz.

N5 Call

The mean for the N5 call's average frequency without noise was 1.073 kHz $\pm$ 0.087 kHz, and with noise it was 1.062 kHz $\pm$ 0.087 kHz (See Table 5.4 and Figure B.5). The results from the Mann-Whitney U test (See Table 5.5) show no significant difference in average

N4 Call - Mann-Whitney U Test Results

Variable	Z	p-level
Average frequency	1.489027	.136490
Number of harmonics	.887244	.374954
Duration	.143348	.886016
Peak duration	.879529	.379121

Table 5.2: Results from Mann-Whitney U Tests for N4 Call Variables. The results from the Mann-Whitney U test comparing the spectral characteristics of the N4 call with and without boat noise.

N4 Call - Kolmogorov-Smirnov Test Results

Variable	p-level
Average frequency	$p<.05$
Number of harmonics	$p>.10$
Duration	$p>.10$
Peak duration	$p>.10$

Table 5.3: Results from Kolmogorov-Smirnov Tests for N4 Call Variables. The results from the Kolmogorov-Smirnov test comparing the spectral characteristics of the N4 call with and without boat noise.

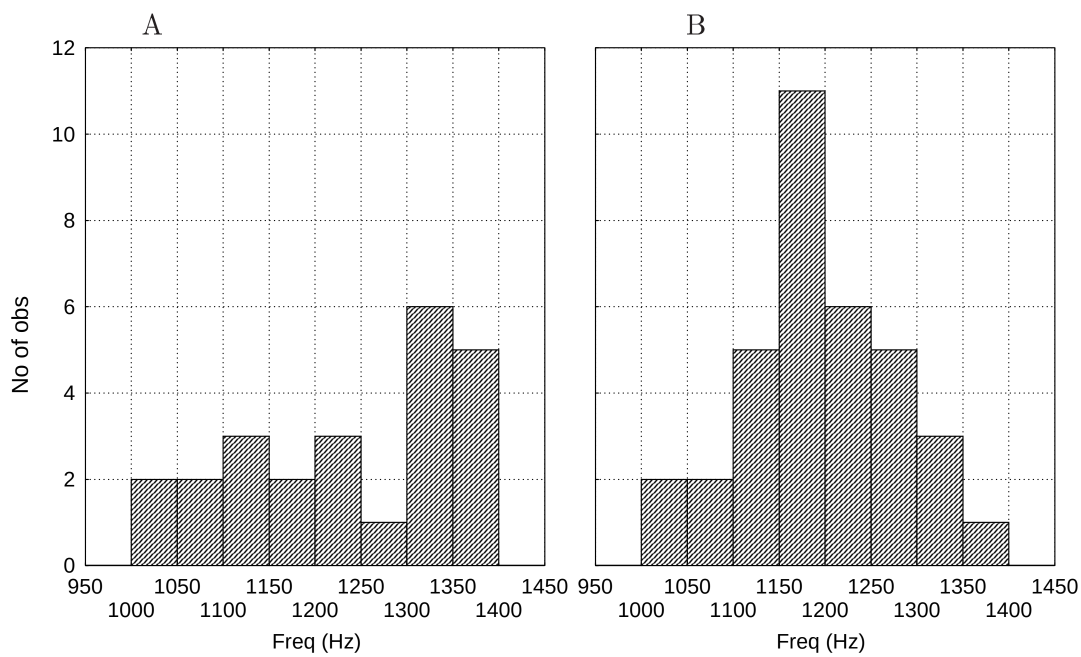

Figure 5.1: Histograms: N4 Call's Average Frequency of the First Harmonic. Histograms for the Average Frequency of the First Harmonic of the N4 call with noise (A) and without noise (B).

N5 Call

Average Frequency

	n	mean (kHz)	median (kHz)	std dev
no boat noise	23	1.073	1.082	0.087
boat noise	27	1.062	1.082	0.087

Number of Harmonics

	n	mean (s)	median (s)	std dev
no boat noise	23	6.652	7.0	2.248
boat noise	27	5.518	5.0	2.326

Duration

	n	mean (s)	median (s)	std dev
no boat noise	23	1.161	1.135	0.246
boat noise	27	1.145	1.036	0.387

Table 5.4: Descriptive Statistics N5 Call. Descriptive statistics of the N5 call's average frequency of the first harmonic, number of harmonics, and duration of the call with and without boat noise.

frequencies for the N5 call with and without boat noise (z=.593690, p-level=.552724). The results from the Kolmogorov-Smirnov test (See Table 5.6) also show no significant difference in the distributions of the two groups. The average frequency of the N5 call, therefore, does not show any detectable modification when in the presence of boat noise.

5.1.2 Number of Harmonics

Each orca call has many harmonics. I tested whether numbers of harmonics in a specific call were different in quiet waters or in noisy waters. I thought that perhaps the orcas could be increasing the number of harmonics of their calls while in the presence of intense motor boat noise in order to make the call more rich sounding and perhaps more detectable over the noise. The data from these calculations can be seen in Table A.4.

N5 Call - Mann-Whitney U Test Results

Variable	Z	p-level
Average frequency	.593690	.552724
Number of harmonics	1.654545	.098027
Duration	.807807	.419207

Table 5.5: Results from Mann-Whitney U Tests for N5 Call Variables. The results from the Mann-Whitney U test comparing the spectral characteristics of the N5 call with and without boat noise.

N5 Call - Kolmogorov-Smirnov Test Results

Variable	p-level
Average frequency	p>.10
Number of harmonics	p>.10
Duration	p>.10

Table 5.6: Results from Kolmogorov-Smirnov Tests for N5 Call Variables. The results from the Kolmogorov-Smirnov test comparing the spectral characteristics of the N5 call with and without boat noise.

N4 Call

The number of harmonics of an N4 call without boat noise was found to have a mean of 6.958 ± 2.804, while the number of harmonics for an N4 call with noise had a similar mean of 6.086 ± 1.686 (See Table 5.1 and Figure B.2). The results from the Mann-Whitney U test (See Table 5.2) found no significant difference when comparing medians of the two groups (z=.887244, p-level=.374954), and the Kolmogorov-Smirnov test also found no significant difference in comparing the distributions of the two groups (See Table 5.3).

N5 Call

The mean for the number of harmonics of the N5 call without boat noise was 6.652 ± 2.248. (See Table 5.4 and Figure 5.2). The mean for the number of harmonics with boat noise

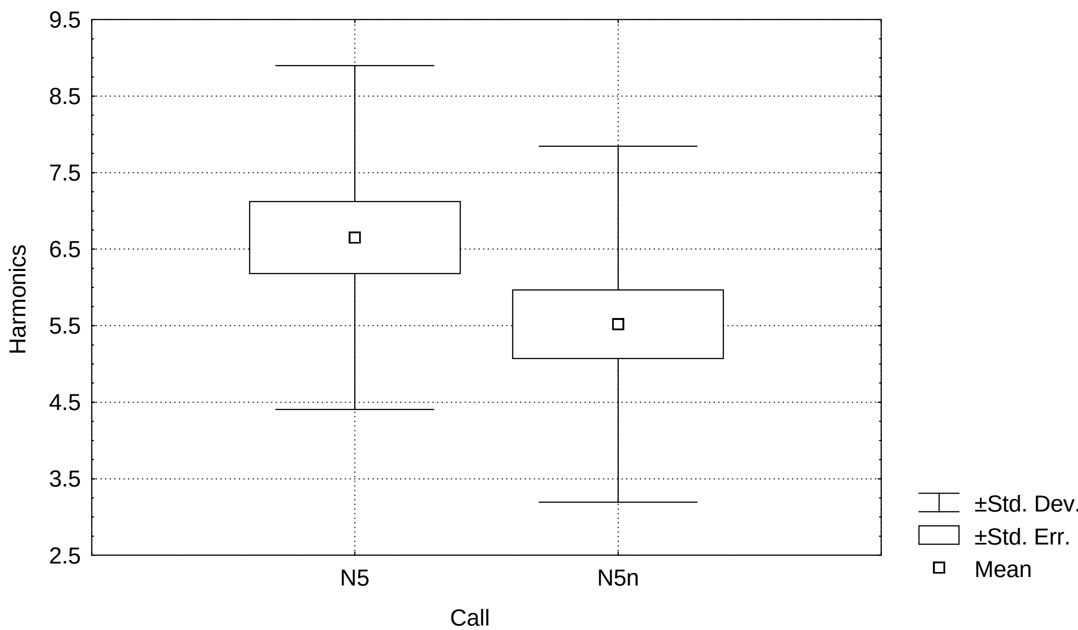

Figure 5.2: Boxplot: N5 Call Harmonics. The boxplots comparing the number of harmonics in the N5 call without and with boat noise.

was 5.519 $\pm$ 2.327. The results from the Mann-Whitney U test (See Table 5.5) do show a significant difference between the medians of the N5 call's number of harmonics with and without boat noise (z=1.654545, p-level=.098027). The N5 call without boat noise has a median of 7 harmonics, while with boat noise, the median is 5 harmonics. The Kolmogorov-Smirnov test, however, shows no difference between the histograms of the two groups (See Table 5.6). Both histograms show peaks at around 4 and 7 harmonics.

5.1.3 Duration of the Call

When making the spectrograms of individual calls, I noticed that the duration of each orca call is fairly consistent. Most calls seem to last about one second. To test for small differences in duration, I used Matlab to find durations for each call, so that I could then statistically compare these durations. To find the duration of each call, I used the improfile command to manually draw a line from the start to the end of the call. From this line on the spectrogram, Matlab would calculate the duration in seconds. Thus, the duration of each individual call was calculated visually and manually by the call's spectrogram. By using Matlab, the durations could be calculated in a more precise and consistent manner. The data from these calculations can be seen in Table A.5.

N4 Call

The mean for the N4 call's duration without boat noise was 1.015 ± 0.194 seconds, while the mean for the duration with noise was similar at 1.012 ± 0.185 seconds (See Table 5.1 and Figure B.3). The results from the Mann-Whitney U test (See Table 5.2) show no significant difference between the medians of the N4 call's duration with and without boat noise (z=.807807, p-level=.419207). The Kolmogorov-Smirnov test also shows no significant difference between the distributions of the two groups (See Table 5.3). The duration of the N4 call was not found to have any change due to boat noise.

N5 Call

The mean for the N5 call's duration when without boat noise was found to be 1.161 ± 0.246 seconds, and the mean for duration with boat noise was 1.145 ± 0.387 seconds (See Table 5.4 and Figure B.7). The results from the Mann-Whitney U test (See Table 5.5) again found no significant difference when comparing the two groups (z=.143384, p-level=.886016). The Kolmogorov-Smirnov test also found no significant difference in comparing the distributions of the two groups (See Table 5.6).

5.1.4 Duration of the Peak

The N4 call, as can be seen from its spectrogram (Figure 4.4), has a peak in its frequency at the beginning of the call. The duration of this peak from the start of the call to the highest point in the peak was measured. Using the improfile command in Matlab, I used the mouse to draw a line on the spectrogram from the start of the call to the distance where the peak of the call was at its highest. Thus, the call's start point and the point where the peak was highest were both defined visually using my own eyes. This was done three separate times to get rid of bias, and an average was taken of the three durations. I wanted to test whether, in the presence of boat noise, the orca modulated the duration of this peak in frequency in order to somehow decrease masking of the call. The data from these calculations can be seen in Table A.6.

N1 Call Average Frequency				N7 Call Average Frequency			
	n	mean (kHz)	std dev		n	mean (kHz)	std dev
no boat noise	9	1.117	0.365	no boat noise	8	1.175	0.137
boat noise	6	1.234	0.452	boat noise	10	1.365	0.334
Number of Harmonics				Number of Harmonics			
	n	mean (s)	std dev		n	mean (s)	std dev
no boat noise	9	12.888	5.134	no boat noise	8	6.625	2.825
boat noise	6	8.000	1.095	boat noise	10	6.000	0.942
Duration				Duration			
	n	mean (s)	std dev		n	mean (s)	std dev
no boat noise	9	1.094	0.378	no boat noise	8	0.890	0.176
boat noise	6	0.836	0.192	boat noise	10	1.120	0.177
Peak Duration				Section Duration			
	n	mean (s)	std dev		n	mean (s)	std dev
no boat noise	9	0.137	0.060	no boat noise	8	0.295	0.084
boat noise	6	0.206	0.292	boat noise	10	0.298	0.076

Table 5.7: Descriptive Statistics N1 and N7 Calls. Descriptive statistics of the average frequency, number of harmonics, duration, duration of the peak and duration of the first section in the N4 and N7 calls with and without boat noise.

N4 Call

The mean peak duration without boat noise was 0.134 $\pm$ 0.042 seconds, and the mean peak duration with boat noise was found to be 0.122 $\pm$ 0.035 seconds (See Table 5.1 and Figure B.4). The results from the Mann-Whitney U test (See Table 5.2) found no statistical difference when comparing medians of the two groups (z=.143348, p-level=.886016), and the Kolmogorov-Smirnov test also found no significant difference in comparing the distributions of the two groups (See Table 5.3).

5.1.5 N1 and N7 Calls

Due to the small sample sizes of the N1 and N7 calls, the statistical analyses comparing differences in certain spectral characteristics and in distributions with and without boat noise were not performed. However, data was collected on the average frequency of the first harmonic, the number of harmonics, and the duration of the call for the N1 and N7 calls. I also collected data on the duration of the peak of the N1 call, and the duration of the first section of the call for the N7 call. The data can be seen in Tables A.3, A.4, A.5, A.6, and A.8. From this data, boxplots were produced in order to show the relationship between the two means. Figures B.8, B.9, B.10, and B.11 show the boxplots for the spectral characteristics of the N1 call. Figures B.12, B.13, B.14, and B.15 show the boxplots for the spectral characteristics of the N7 call. I am presenting these results simply as interesting data to consider, but more samples would need to be taken before any statistical analyses can be completed.

5.2 Results of Average Call Rates Analysis

The frequency of occurrence of call types relative to noise for the A36 subpod in the study area has been documented. Results are based on 32 encounters from five years, 1993, 1994, 1996, 1997, and 1998. The transcriptions from the tapes varied from 27 seconds to 27 minutes. Out of the 285 minutes analyzed, there were a total of 1359 calls. Each recording time did not cover the full repertoire of the A36 subpod, but at least some time during all the recordings analyzed each individual call type for the A36 subpod, except for

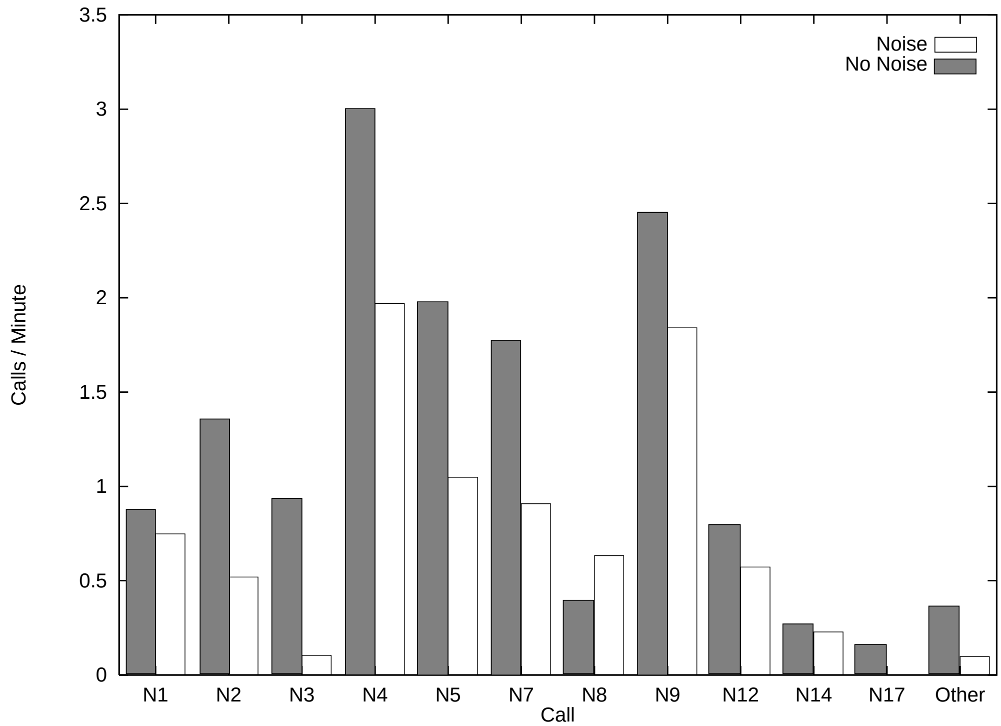

Figure 5.3: Average Call Rates for Individual Call Types. The average call rates (calls/minute) relative to boat noise for each call type made by the A36 subpod.

the N10 call, was produced. Table A.2 shows a complete list of the recording information, listing the total of each call type for that recording time. The percentage use of each call type was calculated taking the total time of each individual recording into consideration.

Call rates of all call types made relative to boat noise is shown in Figure 5.3 and Table A.13. When examining the data from individual calls, each call type almost consistently was emitted more frequently when there was no vessel noise present. This was true for each call type made, with the exception of the N8 call. Figure 5.4 and Table 5.8 show call frequency occurrence again, but only for the total calls with and without boat noise. The data show that, from the 32 recording samples used, the A36 subpod made an average of 10.98 calls per minute when there was no nearby vessel noise, but an average of only 5.82 calls

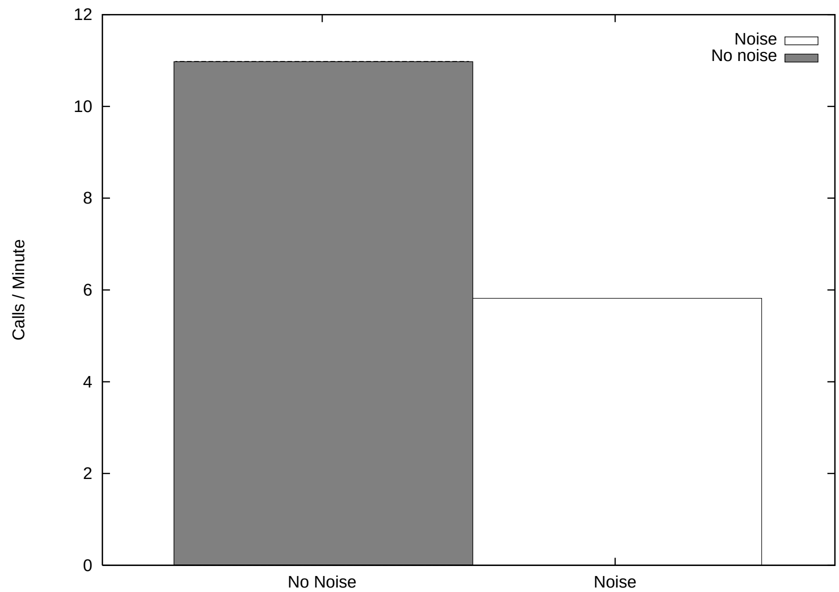

Figure 5.4: Average Call Rates for Total Calls. The call rates (calls/minute) for the total calls with and without boat noise.

Total Calls

	Recording periods	Total time (min.)	Frequency (calls/min)
no boat noise	11	75.58	10.982
boat noise	21	209.78	5.817

Table 5.8: Average Call Rates of Total Calls. The frequency occurrence or average call rate for the total number of calls with and without boat noise.

per minute when there was vessel noise. These results clearly indicate higher vocalization activity on average when there are less auditory disturbances due to nearby vessel noise.

5.3 Analysis of Ambient Noise

After listening to the tapes, calls were characterized as either with or without boat noise qualitatively by ear. The human ear is one of the most accurate ways in which to select specific sounds. In those recordings characterized as with boat noise, motor noise from individual vessels could be heard nearby. In recordings labeled as having no boat noise, only distant vessel noise, natural noise such as water noise on the hydrophone, rain or current noise, or electrical noise from the recording equipment could be heard. It was not difficult to distinguish between the two situations.

Comparing background noise intensities had limitations in this study for several reasons. When the recordings were originally made, assistants at Orcalab would change the gain or amplitude levels as needed. If the orca calls were difficult to hear, the assistant would increase the gain, which also increases noise levels in the recording. This makes it difficult to compare signal or noise levels between different recordings. Also, the hydrophones used were not calibrated, making it impossible to know the exact signal strength of the call at the hydrophone. To further complicate matters, the distance of the calling whale to the hydrophone is unknown, also making it impossible to know the signal strength.

From the digitized data, Matlab calculates the relative amplitudes at each frequency. Because all measurements of decibels are relative, for each individual recording only the ratio of maximum signal intensity to ambient noise intensity could be useful. Unfortunately, this signal to noise ratio can give information about ambient noise levels only if the calling whale is the same distance from the hydrophone in each recording, which most likely was not the case.

5.3.1 Comparing Ambient Noise Levels

With the experiment's limitations in mind, I wanted to show that those calls classified under loud, nearby boat noise conditions really did have greater ambient noise levels. First, I calculated the average background noise intensity levels for all of the N4 calls along a specific frequency. Looking at the spectrogram of an individual call, I used Matlab to draw a horizontal line at the same frequency as the first harmonic. But, this line was drawn before the start of the orca call, so that the only signal the line encompassed was that of background noise. The intensities along this line were then averaged to give the background noise intensity. This background intensity was calculated for each N4 call. Finally, the average background intensity for all N4 calls without boat noise, and the average background intensity for all N4 calls with boat noise were calculated. The result from this exercise was that the average background noise intensity was -18.530 dB for N4 calls without noise, and -14.124 dB for N4 calls with noise, showing an average of a 4 dB difference. Thus, the calls characterized as having boat noise on average have higher ambient noise levels than those calls characterized as having no boat noise. Because of the study limitations mentioned above, the noise levels calculated for each spectrogram are not quantitatable and should not be individually compared. This is the reason I've taken the average of the levels of all calls analyzed, so that at the least, these averages confirm that the calls classified as with boat noise do have higher ambient noise levels.

5.3.2 Comparing Signal to Noise Ratios

As mentioned in subsection 3.2.1, when comparing intensity levels, it is useful to examine the signal to noise ratio (SNR). Again, the SNR is calculated as the difference between the intensity of the signal (or orca call) and the intensity of the background noise. The SNR tells how well a particular signal can be detected over the background noise.

Thus, when there is loud motor noise from a nearby boat, the orca call should be less

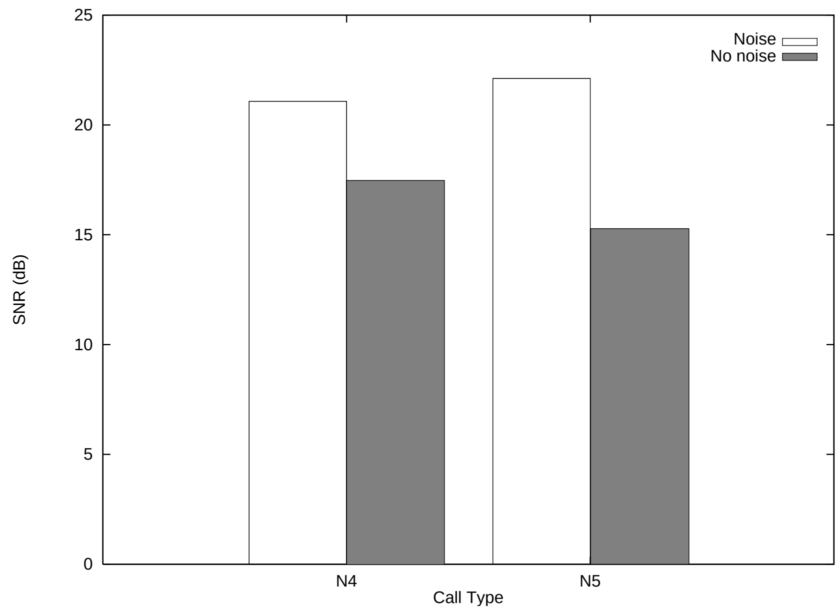

Figure 5.5: Signal to Noise Ratio. The signal to noise ratio for the N4 and N5 calls with and with out boat noise.

detectable, and thus the SNR will be a smaller number. To test this, I calculated the SNR for all N4 and N5 calls with and without boat noise. Using the same method previously explained, the background intensity was calculated for all of the N4 and N5 calls. The average intensity of the first harmonic was also calculated using the same method for each of these calls. The average intensity of the first harmonic was then subtracted by the background noise intensity, giving the SNR for each call. The average of the SNRs was then calculated for N4 calls with and without boat noise, and for N5 calls with and without boat noise. The results can be seen in Table A.9, Table A.10, Table A.11, Table A.12 and Figure 5.5. These results show that the SNR was less for the calls with boat noise, so that the signal was less detectable by a listening whale.

Chapter 6

Conclusions and Discussion

The objective of this study was to identify any differences in vocal behavior of resident British Columbia killer whales associated with the presence of boat noise. The energy in noise emitted from many vessels in the study area is concentrated between 1 Hz and 4 kHz (Figure 4.3). This frequency range is also part of the frequency range of the killer whale discrete calls, which on average range from 1-6 kHz, with harmonics extending up to 10 kHz. Since the boat noise and orca vocalizations overlap, some masking of the whale calls could occur. I proposed that vocalization differences in the presence of boat noise might be indicators of disturbance, and that the whales may be varying some characteristics of their calls in order to reduce the masking effects of boat noise. Previous studies of anthropogenic disturbances to killer whales have focused on changes in behavior relative to human activity. This study compared structural characteristics, such as differences in frequency, duration, and harmonics, to look for differences in the spectra of individual discrete calls when in the presence of vessel motor noise. This study also compared the call rates of different call types, to see if certain calls were more or less preferred when in quiet or noisy waters.

The results demonstrate that, for the spectral characteristics examined, the discrete calls of killer whales are very stable, and do not show much evidence of change when in a noisy environment. Most of the statistical tests indicated there was no significant difference between vocalizations in noisy and quiet waters. However, differences were found in two of the tests. In analyzing call rates, killer whale vocalizations were found to decrease by about fifty percent when in the presence of boat noise.

6.1 Call Rates

The British Columbia resident killer whale is an extremely social animal, remaining with its maternal group for life. These whales rest, play, socialize, travel, and hunt for food while swimming up and down the many different rocky coasts, bays, inlets, and straits of the area. The entire time they keep in vocal contact with their group and are never separated for very long. Communication through discrete calls is important to these whales' social structure. Understanding how vessel noise causes changes in vocal behavior is important in knowing what kind of impact human activity has on these animals.

Results from the call rate analysis clearly indicated lower vocalization activity in the presence of vessel noise. This suggests that at some time during the vessel noise recording periods, the whales were calling less frequently. It is not known whether there is an overall decrease in vocalizing, or if at some specific time, such as when they first hear the vessel noise, the whales are becoming quieter. Boat noise was similarly found to decrease call rates in beluga whales [*Lesage* et al., 1993]. Perhaps this decreased calling is due to the whales listening or paying attention to the location of boats and calling less to each other. Or, perhaps the whales are calling less in order to hear other individuals over the noise.

6.2 Spectral Characteristics

From the examination of changes in call spectral structure, a significant difference was found in the medians of the number of harmonics for an N5 call with and without boat noise. The decreased number of harmonics in the N5 calls in the presence of boat noise could be due to a greater masking of the call due to the loud boat noise. It must be emphasized however, that a lower number of harmonics could be due to the whale facing a different direction from the hydrophone while calling. The decrease in harmonics when there was loud boat noise also could be due to the recording equipment not picking up a softer sound (the orca's call) when there are louder sounds (boat noise) present. Thus, it is hard to speculate what this decrease in harmonics might mean.

There also was a significant difference in the distribution of the N4 call's average frequency with and without noise. The average frequency of the N4 call without noise had a more rectangular distribution, meaning that a greater range of frequencies was used when there was no noise. When in the presence of nearby boat noise, the average frequency of the call had a more peaked distribution, centering around 1175 Hz. It is not known why the whales would center their N4 calls around a specific frequency in the presence of boat noise. The frequencies of the boat noise overlap with frequencies of the whale vocalizations. Perhaps the whales centered their calls around a specific frequency in order to use a frequency that does not correspond with the frequencies of the noise that contain the greatest energy. As discussed earlier, *Lesage* et al. [1993] found that beluga whales alter the frequency characteristics of their vocalizations in order to reduce the masking effects of noise.

The results were not what I would expect from a vocalizing whale trying to reduce the effects of noise. I would have expected the average frequency of the calls with boat noise to shift upward to a frequency above the frequency band containing noise. However, it would be beneficial for the whales to continue calling at lower frequencies since low frequencies will propagate a longer distance underwater. *Au and Penner* [1981], in a study of bottlenose dolphins, also found that the cetaceans did not shift their frequencies away from ambient noise frequencies. They suggest that the dolphins are instead putting the maximum energy of their vocalizations into another frequency range. Increasing signal intensity so it does not correspond with peaks in the noise spectra would make the signal easier to detect by increasing the signal to noise ratio at the receiving whale. Unfortunately, increasing signal intensity could not be examined due to limitations of this study.

Possibly the whales have become tolerant of the frequent boat noise in the area. These killer whales are often seen moving away from an area with heavy boat traffic, but they also are often seen tolerating nearby disturbances from boat traffic. This may be because no other area can supply them with what they need, or because their behavior patterns were developed long before there were any human disturbances. The whales could be showing no disturbance reaction simply because the noise is insignificant and does not bother them. It is also likely that the whale's tolerance to nearby boat traffic is due to a gradual habituation to the disturbances that has happened over the course of many years.

Although these orcas show little change in their vocalizations in reaction to vessels, behavior changes have been observed in past studies. Some changes include increasing swim speeds, swimming erratically, and changing direction of travel when vessels are nearby [*Williams*, 1999; *Kruse*, 1985]. Although these orcas have a good chance of habituating to these vessel disturbances, it is possible that there are unknown negative effects. If these incidents cause repeated disturbance, such as continuously raised stress levels, or less time spent in optimal feeding areas, there may be long-term health effects. There is also concern that these whales, if subject to ongoing stress, may eventually show long-term displacement from the area. Humpback whales have been documented avoiding certain previously used coastal areas off Hawaii where human activities are intense [*Salden*, 1988]. Grey whales have been documented abandoning a calving lagoon off of California temporarily while vessel traffic in that area was high *Reeves* [1977]. More information on vocalization function and purpose, boat noise levels, possible masking effects, and possible adaptions killer whales use to cope with noise is necessary before further conclusions can be made.

6.3 Complications of the Study

Any differences found between two sets of calls may have been caused by some other factor besides the boat noise. First, there may be significant differences between the calls of individual killer whales due to age, social status, or sex of the individual. This could cause bias in the measurements. Also, perhaps the whales' behavior at any time causes subtle differences in their vocalizations. Change in call structure may be influenced by a killer whale traveling, playing, or socializing, or even by overall activity level. Having other orcas around, such as another subpod, is another variable that may have an effect on call structure, since when different subpods meet there is often socializing, excitement and increased vocalizing. In regards to boat noise, the different types of vessel noise may have different effects on the whales. For example, the whales could have habituated to a particular type of boat noise, causing little to no vocal difference in response to that noise, while another type of boat noise may be very disturbing to the whales. Last, differences found in the calls may also be influenced by non-boat noise. Natural noises such as wind, precipitation, and currents also may have an effect on the killer whale vocalizations, causing biases in the measurements.

I tried to eliminate some of these variables. For example, interference in the study due to the A36 subpod socializing or communicating with another subpod was eliminated in that I examined only those recording times when the A36 subpod was alone in the study area. This presented a problem in that it greatly limited the amount of recordings I could use. The A36 subpod is much less vocal when alone than when there is another group of orcas around. Since they were less vocal, this contributed to limiting the sample size, because there were fewer suitable calls to choose from. Differences due to seasonality were eliminated by analyzing vocalizations from recordings taken in the summer and late summer months only.

My findings show that the discrete calls of northern resident British Columbia killer whales overall are not altered when there are loud boat noises. This study raises interesting questions about how future research could be conducted. Perhaps I did not look at the right spectral characteristics for each call, or perhaps I did not look at the right types of calls. How could future studies be carried out in order to eliminate other variables that could bias the measurements, and what methods could be used in order to better control the experiment?

6.4 Suggestions for Future Research

In the course of completing this research, I became more aware of many steps that could be taken in order to make a stronger study. I have come to think of this study more as a pilot project for future research on killer whale vocal behavior, with emphasis on disturbances due to underwater vessel noise. The next few paragraphs give ideas to be used in designing and executing future, similar studies.

First, calls should be tested for independence. Since there is no obvious evidence of dependency in orca calls, I assumed the observations were independent. If the orcas have some unknown pattern of calls, in which, after a certain sequence of calls the next call is altered, then this needs to be examined. One way to investigate this would be to test lists of calls in a sequence and test them against calls 5 minutes later, to see if there are any dependent tendencies.

Something that would be useful, if not essential, in an analysis of killer whale calls would be to identify the location of the calling whale. This is extremely important because knowledge of the distance between the whale and the hydrophone can be used to measure and compare intensity levels of the vocalization. The whales may be increasing their vocalization rates in order to reduce masking effects caused by the vessel noise. One method would be to use an array of hydrophones to find the location of the animal and the motorboat by triangulation. A second method would be to use a Theolodite tracker as in the study by *Kruse* [1991].

Another recommendation for future research is to have more control over the vessel noise. Since I did not have control over the noise source, I was not able to monitor intensity of the noise. Future studies should involve an analysis of the boat noise, measuring the distance from the vessel to the whale, and the intensities of noise at varying distances from its source. Thus, the noise levels near the animals being recorded could be estimated.

In a similar study, it would also be advisable to take a much larger sample size to ensure sound statistical results. In order to get a large sample size, many more recordings will need to be analyzed. A benefit of using more recordings is that you could ensure that all samples of calls categorized as 'with noise' have relatively large amounts of noise compared with the 'no noise' calls. And the 'no noise' calls should ideally have very little natural and man-made noise in the background. These steps would help to limit any biasing that may occur.

As mentioned previously in this thesis, researchers should consider a detailed comparison of vocal differences taking into consideration the aspect of the boat relative to the calling whale. Perhaps, if the boat is directly in front of, or to the side of the vocalizing whale, the whale may alter its vocalizations to decrease masking effects. *Bain and Dahlheim* [1994] found that the location of the boat relative to the whale makes a great difference in whether or not the calls are masked. Thus, the location of the boat may make a great difference in there being any spectral differences in killer whale vocalizations.

Perhaps killer whales do not alter their calls in order to better communicate above the high levels of vessel noise that so frequently accompany the orcas in the study area. Possibly, their complex vocalizations and hearing abilities are already able to overcome most masking effects caused by noise. However, since we do not have a full understanding of the long and short-term effects of noise on these animals, it is wise to take steps towards a complete understanding of possible disturbances.

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Appendix A

Tables of Data

The table present all the data used in this thesis. Table A.1 is a list of each individual call used in the analysis. This table shows the tape number and call number for each individual call, as well as the date that recording was made and the time on the tape that call can be found. Table A.2 is a master description of all recordings. This table breaks the recordings down into specific times when calling whales were present and gives the number of each call type made as well as the total time of that recording period. Table A.3 shows data for the average frequency of the first harmonic of the N1, N4, N5, and N7 calls. Table A.4 shows the data for the number of harmonics for each calls. Table A.5 shows the duration in seconds for each call. Table A.6 shows the duration of the frequency peak of the N4 call, and Table A.7 shows the data for the duration of the frequency peak of the N1 call. The duration of the frequency peak is measured from the start of the call to the highest point in the peak. Table A.8 shows the duration of the first lower frequency, broad-band section of the N7 call. Tables A.9, A.10, A.11 and A.12 show data on the average intensity levels (dB) for the N4 and N5 calls with and without noise. Average intensity levels were calculated for the first harmonic of each call (signal mean intensity) and the ambient noise of each call (noise mean intensity). From these the signal to noise ratio was calculated. Table A.13 shows the average call rate for each individual call and for the total calls for the A36 subpod.

Call Type	Tape and Call Number	Date	Tape Time
N4	259A_3	9/26/94	3425
N4	258B_4	9/24/94	3223
N4	258B_3	9/24/94	3208
N4	146A_20	9/19/97	750
N4	146A_15	9/19/97	651
N4	145A_9	9/18/97	4539
N4	145A_8	9/18/97	4538
N4	201A_6	8/18/94	1849
N4	145A_10	9/18/97	4541
N4	145A_13	9/18/97	1843
N4	145A_3	9/18/97	3219
N4	145A_2	9/18/97	2542
N4	146A_13	9/19/97	2630
N4	146A_9	9/19/97	2418
N4	146A_7	9/19/97	2351
N4	146A_5	9/19/97	2255
N4	146A_3	9/19/97	2142
N4	146A_2	9/19/97	2124
N4	215A_8	8/25/94	2728
N4	215A_4	8/25/94	2442
N4	215A_2	8/25/94	1110
N4	201A_2	8/18/94	1708
N4	201A_1	8/18/94	1645
N4	146A_14	9/19/97	2635
N4n	250B_1	9/10/94	4126
N4n	490A_5	9/28/96	4423
N4n	490A_4	9/28/96	4412
N4n	490A_3	9/28/96	4955
N4n	255A_2	9/17/94	2310
N4n	490A_1	9/28/96	4350
N4n	215A_14	8/25/94	3931
N4n	215A_13	8/25/94	3930
N4n	215A_12	8/25/94	3822
N4n	205B_13	8/20/94	2621
N4n	205B_12	8/20/94	2501
N4n	205B_11	8/20/94	2320
N4n	205B_10	8/20/94	2500
N4n	257B_3	9/24/94	1337
N4n	146A_1	9/19/97	3940
N4n	250B_3	9/10/94	4153

Table A.1: Individual Calls Analyzed. Information about the individual calls recorded and analyzed.

Call Type	Tape and Call Number	Date	Tape Time
N4n	250B_5	9/10/94	4239
N4n	214B_8	8/25/94	1620
N4n	214B_9	8/25/94	1625
N4n	146A_16	9/19/97	713
N4n	146A_19	9/19/97	823
N4n	355B_9	8/19/98	4126
N4n	258A_1	9/24/94	649
N4n	258A_2	9/24/94	3816
N4n	255A_1	9/18/94	2303
N4n	490A_2	9/28/96	4954
N4n	256B_2	9/21/94	439
N4n	257B_1	9/24/94	1208
N4n	257B_2	9/24/94	1217
N4n	250B_2	9/10/94	4135
N4n	214B_4	8/25/94	2638
N4n	205B_6	8/20/94	2635
N4n	205B_4	8/20/94	2614
N4n	205B_5	8/20/94	2623
N5	146A_10	9/19/97	2450
N5	490B_4	9/28/96	3215
N5	214A_1	8/25/94	4617
N5	145A_18	9/18/97	1143
N5	145A_17	9/18/97	1144
N5	145A_16	9/18/97	1141
N5	145A_15	9/18/97	751
N5	145A_14	9/18/97	736
N5	215A_3	8/25/94	1118
N5	214B_11	8/25/94	3226
N5	215A_5	8/25/94	2527
N5	214B_10	8/25/94	3218
N5	215A_6	8/25/94	2551
N5	259A_2	9/26/94	3401
N5	146A_11	9/19/97	2451
N5	259A_1	9/26/94	3344
N5	145A_1	9/18/97	2407
N5	258B_6	9/24/94	3305
N5	258B_5	9/24/94	3247
N5	201A_13	8/18/94	2444
N5	201A_12	8/18/94	2432
N5	201A_11	8/18/94	2430
N5	145A_4	9/18/97	4200

Table A.1: Individual Calls Analyzed. Information about the individual calls recorded and analyzed.

Call Type	Tape and Call Number	Date	Tape Time
N5n	492A_1	9/28/96	524
N5n	490B_3	9/28/96	349
N5n	490B_2	9/28/96	242
N5n	490B_1	9/28/96	238
N5n	241B_3	9/5/94	4122
N5n	241B_2	9/5/94	4225
N5n	205A_1	8/20/94	4213
N5n	215A_10	8/25/94	3620
N5n	205B_2	8/20/94	2236
N5n	146A_2	9/19/97	4013
N5n	445A_1	9/18/93	4629
N5n	255A_3	9/18/94	2332
N5n	355B_5	8/19/98	2856
N5n	355B_4	8/19/98	2843
N5n	355B_3	8/19/98	2842
N5n	355B_1	8/19/98	2150
N5n	201A_7	8/18/94	1858
N5n	146A_18	9/19/97	743
N5n	146A_17	9/19/97	734
N5n	214B_7	8/25/94	1618
N5n	214B_6	8/25/94	1556
N5n	250B_13	9/10/94	4613
N5n	250B_12	9/10/94	4541
N5n	250B_9	9/10/94	4501
N5n	214B_3	8/25/94	2551
N5n	214B_1	8/25/94	2401
N5n	241B_4	9/5/94	4313
N7	201A_3	8/18/94	1637
N7	201A_4	8/18/94	1729
N7	145A_6	9/18/97	4218
N7	145A_5	9/18/97	4215
N7	145A_7	9/18/97	4220
N7	201A_5	8/18/94	1837
N7	201A_9	8/18/94	2320
N7	201A_10	8/18/94	2325
N7n	205B_7.1	8/20/94	2641
N7n	205B_7.2	8/20/94	2642
N7n	205B_8	8/20/94	2700
N7n	205B_9	8/20/94	2706
N7n	250B_4	9/10/94	4159
N7n	250B_6	9/10/94	4326

Table A.1: Individual Calls Analyzed. Information about the individual calls recorded and analyzed.

Call Type	Tape and Call Number	Date	Tape Time
N7n	250B_7	9/10/94	4414
N7n	250B_8	9/10/94	4416
N7n	250B_10	9/10/94	4532
N7n	241A_1	9/5/94	4418
N1	215A_7	8/25/94	2623
N1	146A_6	9/19/97	2330
N1	146A_8	9/19/97	2352
N1	145A_11	9/18/97	4623
N1	145A_12	9/18/97	4637
N1	446A_1	9/18/93	1742
N1	446A_2	9/18/93	1744
N1	446A_4	9/18/93	1746
N1	446A_5	9/18/93	1739
N1n	205B_3	8/20/94	2349
N1n	214B_2	8/25/94	2520
N1n	355B_6	8/19/98	4022
N1n	241B_1	9/5/94	447
N1n	146A_1	9/19/97	2123
N1n	205B_9	8/20/94	2349

Table A.1: Individual Calls Analyzed. Information about the individual calls recorded and analyzed.

1993																	
Tape	Tape Time	Total Time	N1	N2	N3	N4	N5	N7	N8	N9	N10	N12	N43	N47	other	Total Calls	Noise
445A	3247-4700	14:13	3	7	0	6	11	0	0	4	0	0	0	0	0	31	2
446A	0513-0540	00:27	0	0	0	3	0	2	0	0	0	0	0	0	0	5	2
446A	1551-2240	06:49	11	14	0	30	19	2	0	37	0	0	0	0	0	113	4
446A	3645-4305	06:20	0	3	0	1	0	0	0	3	0	0	0	0	0	7	2
446A	4305-4723	04:18	0	2	0	11	6	1	0	4	0	1	0	0	1	26	4

1994																	
Tape	Tape Time	Total Time	N1	N2	N3	N4	N5	N7	N8	N9	N10	N12	N43	N47	other	Total Calls	Noise
201A	1645-1849	02:05	0	5	1	5	10	7	0	15	0	1	1	0	0	45	0
201A	1855-2548	06:53	0	2	1	1	7	0	9	0	0	9	0	0	0	20	2
204A	3316-3834	05:18	0	2	0	3	2	0	0	5	0	0	0	0	0	23	4
204B	0439-0941	05:02	3	5	0	11	11	0	0	12	0	0	0	0	0	42	4
205B	2345-3030	06:45	1	1	0	11	3	5	0	1	0	0	0	0	0	22	2
214B	2329-3934	16:05	16	5	0	29	26	10	0	27	0	0	2	0	1	118	3
215A	0747-1214	04:27	0	11	9	13	14	5	0	13	0	0	0	0	0	63	0
215A	2323-2642	03:19	3	5	0	11	10	0	0	19	0	0	0	0	0	48	0
215A	3610-3930	03:20	3	11	0	8	4	5	1	3	0	0	0	0	0	35	0
255A	2303-2550	02:47	1	0	0	10	7	3	0	21	0	0	0	0	0	43	1
256B	0436-0458	00:22	0	0	0	3	0	0	0	1	0	0	0	0	0	4	1
256B	2252-3600	13:08	3	0	1	9	7	2	0	9	0	0	0	0	0	31	2
257B	1158-1738	05:40	1	0	0	22	2	3	0	12	0	1	0	0	0	44	2
258A	0026-2042	20:16	3	2	0	21	1	12	4	22	0	0	0	0	1	67	3
258A	2042-2442	04:00	1	0	0	4	0	9	4	3	0	4	0	0	0	25	0
258B	1955-3217	22:22	0	4	2	13	2	0	0	8	0	0	0	0	0	29	3
258B	3217-4010	07:43	0	0	0	2	11	0	0	3	0	0	0	0	0	25	0

1996																	
Tape	Tape Time	Total Time	N1	N2	N3	N4	N5	N7	N8	N9	N10	N12	N43	N47	other	Total Calls	Noise
490A	4050-4726	06:36	1	1	0	8	0	0	0	7	0	0	0	0	0	17	2
492A	0026-2146	21:20	11	1	0	8	8	0	0	3	0	0	0	0	0	31	3
492B	0530-2659	21:29	1	0	0	17	13	0	0	4	0	0	0	0	0	31	4

1997																	
Tape	Tape Time	Total Time	N1	N2	N3	N4	N5	N7	N8	N9	N10	N12	N43	N47	other	Total Calls	Noise
145A(2)	1922-4701	27:39	12	2	0	47	6	23	10	21	0	0	0	0	0	127	0
145A(3)	1123-1355	02:32	0	3	0	1	6	1	1	17	0	0	0	0	0	29	1
146A(1)	3940-4700	07:20	1	0	0	15	2	0	0	6	0	9	2	0	3	29	0
146A(2)	0627-1312	06:25	0	2	0	42	10	3	1	17	0	0	1	0	0	76	0
146A(2)	1719-2330	06:11	4	1	2	31	6	19	1	8	0	3	1	1	2	79	0
146A(2)	2330-2636	03:06	9	2	0	17	10	5	0	11	0	0	0	0	0	54	0

1997																	
Tape	Tape Time	Total Time	N1	N2	N3	N4	N5	N7	N8	N9	N10	N12	N43	N47	other	Total Calls	Noise
355B	2152-4257	21:05	1	0	0	2	7	0	0	2	0	0	7	0	1	20	4

Table A.2: Information on Recordings Used for Call Percentages. Data on the recordings used and individual calls in each recording for the comparison of percent of each call type when there is and is not boat noise. The ‘Noise’ column is a qualitative scale from 0-4 which rates levels of boat noise where 0 = no boat noise, 1 = soft boat noise, 2 = moderate boat noise, 3 = loud boat noise, and 4 = extremely loud boat noise.

Average Frequency of the First Harmonic of the Call															
N4 Call	Freq (Hz)	N4/noise Call	Freq (Hz)	N5 Call	Freq (Hz)	N5/noise Call	Freq (Hz)	N1 Call	Freq (Hz)	N1/noise Call	Freq (Hz)	N7 Call	Freq (Hz)	N7/noise Call	Freq (Hz)
259A 3	1367	250B 1	1224	146A 10	834	492A 1	1101	215A 7	1745	205B 3	1833	201A 3	1329	205B 7.1	1197
258B 4	1271	490A 5	1221	490B 4	891	490B 3	1159	146A 6	882	214B 2	923	201A 4	1263	205B 7.2	1285
258B 3	1203	490A 4	1302	214A 1	1178	490B 2	1159	146A 8	903	355B 6	932	145A 6	1163	205B 8	1346
146A 20	1337	490A 3	1298	145A 18	1058	490B 1	1086	145A 11	924	241B 1	1003	145A 5	1175	205B 9	1197
146A 15	1309	255A 2	1128	145A 17	1178	241B 3	1129	145A 12	900	146A 1	914	145A 7	862	250B 4	1310
145A 9	1077	490A 1	1213	145A 16	1149	241B 2	1044	446A 1	995	205B 9	1802	201A 5	1219	250B 6	1329
145A 8	1157	215A 14	1096	145A 15	1082	205A 1	1159	446A 2	955			201A 9	1197	250B 7	1042
201A 6	1004	215A 13	1166	145A 14	1147	215A 10	1165	446A 4	1772			201A 10	1197	250B 8	1263
145A 10	1063	215A 12	1140	215A 3	1178	205B 2	1108	446A 5	984					250B 10	2273
145A 13	1224	205B 13	1190	214B 11	1063	146A 2	1127							241A 1	1413
145A 3	1161	205B 12	1228	215A 5	1140	445A 1	1056								
145A 2	1131	205B 11	1252	214B 10	1094	255A 3	1025								
146A 13	1329	205B 10	1309	215A 6	1075	355B 5	929								
146A 9	1326	257B 3	1199	259A 2	1123	355B 4	968								
146A 7	1150	146A 1	1367	146A 11	1063	355B 3	1102								
146A 5	1324	250B 3	1167	259A 1	1140	355B 1	982								
146A 3	1369	250B 5	1233	145A 1	1001	201A 7	962								
146A 2	1350	214B 8	1103	258B 6	986	146A 18	1082								
215A 8	1368	214B 9	1180	258B 5	1001	146A 17	1234								
215A 4	1226	146A 16	1163	201A 13	1082	214B 7	1018								
215A 2	1351	146A 19	1251	201A 12	1101	214B 6	989								
201A 2	1010	355B 9	1179	201A 11	1102	250B 13	907								
201A 1	1106	258A 1	1317	145A 4	1030	250B 12	932								
146A 14	1376	258A 2	1050			250B 9	974								
		255A 1	1097			214B 3	1109								
		490A 2	1274			214B 1	1012								
		256B 2	1146			241B 4	1159								
		257B 1	1147												
		257B 2	1218												
		250B 2	1151												
		214B 4	1173												
		205B 6	1264												
		205B 4	1182												
		205B 5	1197												
		256B 1	1050												

Table A.3: Average Frequency of the First Harmonic. Data taken for the average frequency of the first harmonic for the N1, N4, N5, and N7 calls.

Number of Harmonics in the Call															
N4 call	Harmonics	N4/noise call	Harmonics	N5 call	Harmonics	N5/noise call	Harmonics	N1 call	Harmonics	N1/noise call	Harmonics	N7 call	Harmonics	N7/noise call	Harmonics
259A 3	8	250B 1	7	146A 10	12	492A 1	4	215A 7	3	205B 3	8	201A 3	9	205B 7.1	6
258B 4	5	490A 5	4	490B 4	7	490B 3	4	146A 6	7	214B 2	7	201A 4	10	205B 7.2	6
258B 3	8	490A 4	4	214A 1	7	490B 2	4	146A 8	11	355B 6	10	145A 6	3	205B 8	7
146A 20	7	490A 3	4	145A 18	5	490B 1	3	145A 11	17	241B 1	7	145A 5	3	205B 9	6
146A 15	7	255A 2	3	145A 17	4	241B 3	2	145A 12	18	146A 1	8	145A 7	4	250B 4	6
145A 9	12	490A 1	4	145A 16	4	241B 2	3	446A 1	15	205B 9	8	201A 5	8	250B 6	5
145A 8	11	215A 14	5	145A 15	4	205A 1	2	446A 2	16			201A 9	8	250B 7	7
201A 6	10	215A 13	4	145A 14	6	215A 10	4	446A 4	12			201A 10	8	250B 8	6
145A 10	12	215A 12	4	215A 3	4	205B 2	7	446A 5	17					250B 10	7
145A 13	5	205B 13	7	214B 11	7	146A 2	8							241A 1	4
145A 3	5	205B 12	7	215A 5	4	445A 1	6								
145A 2	6	205B 11	7	214B 10	6	255A 3	4								
146A 13	7	205B 10	7	215A 6	4	355B 5	4								
146A 9	7	257B 3	6	259A 2	8	355B 4	7								
146A 7	5	146A 1	4	146A 11	7	355B 3	7								
146A 5	7	250B 3	7	259A 1	9	355B 1	5								
146A 3	5	250B 5	6	145A 1	10	201A 7	6								
146A 2	6	214B 8	8	258B 6	6	146A 18	7								
215A 8	3	214B 9	8	258B 5	7	146A 17	7								
215A 4	3	146A 16	7	201A 13	7	214B 7	6								
215A 2	3	146A 19	7	201A 12	10	214B 6	10								
201A 2	11	355B 9	8	201A 11	9	250B 13	10								
201A 1	10	258A 1	7	145A 4	6	250B 12	10								
146A 14	4	258A 2	10			250B 9	7								
		255A 1	4			214B 3	5								
		490A 2	4			214B 1	4								
		256B 2	6			241B 4	3								
		257B 1	8												
		257B 2	7												
		250B 2	7												
		214B 4	4												
		205B 6	7												
		205B 4	7												
		205B 5	7												
		256B 1	7												

Table A.4: Number of Harmonics in the Call. Data for the number of harmonics in each call for the N1, N4, N5, and N7 calls.

Duration of the Call															
N4 call	Duration(s)	N4/noise call	Duration(s)	N5 call	Duration(s)	N5/noise call	Duration(s)	N1 call	Duration(s)	N1/noise call	Duration(s)	N7 call	Duration(s)	N7/noise call	Duration(s)
259A 3	0.872	250B 1	1.2032	146A 10	1.5327	492A 1	0.8481	215A 7	1.1887	205B 3	0.7832	201A 3	1.0329	205B 7.1	0.9979
258B 4	1.4418	490A 5	0.9494	490B 4	0.9808	490B 3	0.9537	146A 6	0.8953	214B 2	0.938	201A 4	1.0015	205B 7.2	1.0854
258B 3	1.224	490A 4	0.9643	214A 1	1.4433	490B 2	0.8251	146A 8	1.9819	355B 6	0.612	145A 6	0.6926	205B 8	1.046
146A 20	1.3245	490A 3	0.8595	145A 18	1.0788	490B 1	0.915	145A 11	1.3284	241B 1	0.7358	145A 5	0.996	205B 9	1.3499
146A 15	1.2417	255A 2	0.9702	145A 17	0.9081	241B 3	1.0361	145A 12	1.0424	146A 1	1.1651	145A 7	0.5533	250B 4	1.399
145A 9	1.0565	490A 1	0.7518	145A 16	1.1332	241B 2	0.9234	446A 1	0.8976	205B 9	0.784	201A 5	0.9051	250B 6	1.1488
145A 8	0.8215	215A 14	0.9776	145A 15	1.1358	205A 1	1.0597	446A 2	0.8372			201A 9	0.9054	250B 7	1.0198
201A 6	0.7628	215A 13	0.7624	145A 14	0.7368	215A 10	1.5404	446A 4	0.9312			201A 10	1.0337	250B 8	1.2925
145A 10	1.0004	215A 12	1.193	215A 3	1.2371	205B 2	0.8567	446A 5	0.7487					250B 10	1.0404
145A 13	0.692	205B 13	1.0149	214B 11	1.2643	146A 2	1.355							241A 1	0.8272
145A 3	0.7626	205B 12	0.9788	215A 5	1.5791	445A 1	0.9341								
145A 2	0.9461	205B 11	0.9262	214B 10	1.2373	255A 3	1.0188								
146A 13	0.9558	205B 10	0.9882	215A 6	1.6164	355B 5	0.7084								
146A 9	0.8654	257B 3	0.84	259A 2	0.9619	355B 4	0.8314								
146A 7	1.0574	146A 1	0.8257	146A 11	1.3758	355B 3	0.8356								
146A 5	1.0825	250B 3	0.9888	259A 1	0.9007	355B 1	0.696								
146A 3	1.3316	250B 5	1.1948	145A 1	1.2029	201A 7	0.8723								
146A 2	1.0488	214B 8	1.1263	258B 6	1.3452	146A 18	1.7165								
215A 8	1.102	214B 9	1.0751	258B 5	1.3099	146A 17	1.5355								
215A 4	1.1132	146A 16	1.2724	201A 13	0.8313	214B 7	1.4647								
215A 2	0.9702	146A 19	1.1885	201A 12	0.9655	214B 6	1.1106								
201A 2	0.8419	355B 9	0.8857	201A 11	0.9477	250B 13	1.3685								
201A 1	0.8868	258A 1	0.7631	145A 4	0.9964	250B 12	1.325								
146A 14	0.9589	258A 2	1.5376			250B 9	1.0951								
		255A 1	1.2593			214B 3	2.4979								
		490A 2	0.7436			214B 1	1.3167								
		256B 1	0.9619			241B 4	1.2925								
		256B 2	1.0216												
		257B 1	0.836												
		257B 2	0.8261												
		250B 2	1.277												
		214B 4	1.3567												
		205B 6	1.002												
		205B 4	0.9378												
		205B 5	0.9553												
		256B 1	1.0174												

Table A.5: Duration of the Call. Data taken for the duration in seconds of each call analyzed. The call types include the N1, N4, N5, and N7 calls.

Duration of the Peak of the Call									
N4 call	*Peak Duration 1*	*Peak Duration 2*	*Peak Duration 3*	*Avg Peak Duration*	*N4/Noise call*	*Peak Duration 1*	*Peak Duration 2*	*Peak Duration 3*	*Avg Peak Duration*
259A 3	0.1018	0.1133	0.115	0.1100	250B 1	0.1432	0.1362	0.1306	0.1367
258B 4	0.1875	0.1945	0.1927	0.1916	490A 5	0.1323	0.1431	0.1504	0.1419
258B 3	0.1063	0.1047	0.1047	0.1052	490A 4	0.0991	0.1025	0.1075	0.1030
146A 20	0.1385	0.1319	0.1418	0.1374	490A 3	0.1514	0.1456	0.1442	0.1471
146A 15	0.1451	0.1484	0.1434	0.1456	255A 2	0.1239	0.1473	0.1423	0.1378
145A 9	0.1377	0.1353	0.1317	0.1349	490A 1	0.1034	0.0993	0.1034	0.1020
145A 8	0.1514	0.0763	0.0782	0.1020	215A 14	0.1812	0.1671	0.1696	0.1726
201A 6	0.1593	0.1593	0.1622	0.1603	215A 13	0.0615	0.0852	0.0841	0.0769
145A 10	0.1072	0.1072	0.1108	0.1084	215A 12	0.0847	0.0879	0.0799	0.0842
145A 13	0.1142	0.1125	0.1032	0.1100	205B 13	0.1204	0.1204	0.1123	0.1177
145A 3	0.0773	0.0763	0.0782	0.0773	205B 12	0.1188	0.1175	0.1188	0.1184
145A 2	0.0973	0.1022	0.0912	0.0969	205B 11	0.1254	0.1074	0.1163	0.1164
146A 13	0.1897	0.1808	0.2101	0.1935	205B 10	0.2088	0.2169	0.2134	0.2130
146A 9	0.1107	0.1084	0.1084	0.1092	257B 3	0.1127	0.0996	0.1022	0.1048
146A 7	0.0795	0.0782	0.0861	0.0813	146A 1	0.0932	0.0932	0.0843	0.0902
146A 5	0.2004	0.2033	0.2062	0.2033	250B 3	0.0888	0.0888	0.0929	0.0902
146A 3	0.116	0.1301	0.105	0.1170	250B 5	0.1051	0.1035	0.1099	0.1062
146A 2	0.1415	0.1401	0.1619	0.1478	214B 8	0.1409	0.1394	0.1595	0.1466
215A 8	0.112	0.1164	0.1105	0.1130	214B 9	0.1258	0.1186	0.1229	0.1224
215A 4	0.0845	0.0599	0.0799	0.0748	146A 16	0.1125	0.1159	0.1142	0.1142
215A 2	0.1268	0.1134	0.1089	0.1164	146A 19	0.1451	0.1484	0.1434	0.1456
201A 2	0.2249	0.1889	0.2192	0.211	355B 9	0.1159	0.1178	0.1123	0.1153
201A 1	0.2033	0.2004	0.1946	0.1994	258A 1	0.0665	0.0742	0.0774	0.0727
146A 14	0.1791	0.178	0.1757	0.1776	258A 2	0.142	0.1381	0.14	0.1400
					255A 1	0.2158	0.2178	0.2158	0.2165
					490A 2	0.0814	0.0778	0.0778	0.079
					256B 2	0.1109	0.0958	0.1142	0.1070
					257B 1	0.1119	0.0793	0.0871	0.0928
					257B 2	0.1107	0.0956	0.0834	0.0966
					250B 2	0.1609	0.1592	0.1557	0.1586
					214B 4	0.0814	0.0698	0.0764	0.0759
					205B 6	0.1306	0.1289	0.1255	0.1283
					205B 4	0.1567	0.1462	0.1492	0.1507
					205B 5	0.1067	0.111	0.1081	0.1086
					256B 1	0.1658	0.1581	0.1594	0.1611

Table A.6: Duration of the Peak of the N4 Call. Data on the duration of the peak of the call for all N4 calls. This duration was calculated three separate times, and then an average was taken from these.

Duration of the Peak of the Call									
N1 call	*Peak Duration 1*	*Peak Duration 2*	*Peak Duration 3*	*Avg Peak Duration*	*N1/Noise call*	*Peak Duration 1*	*Peak Duration 2*	*Peak Duration 3*	*Avg Peak Duration*
215A 7	0.0695	0.0617	0.0695	0.0669	205B 3	0.0919	0.087	0.087	0.0886
146A 6	0.0946	0.0873	0.1068	0.0962	214B 2	0.0724	0.0946	0.0752	0.0807
146A 8	0.2039	0.1976	0.2007	0.2007	355B 6	0.1036	0.1036	0.1036	0.1036
145A 11	0.2143	0.2143	0.209	0.2125	241B 1	0.0752	0.1098	0.0772	0.0874
145A 12	0.219	0.2211	0.219	0.2197	146A 1	0.0794	0.0728	0.0772	0.0765
446A 1	0.1289	0.1289	0.1176	0.1251	205B 9	0.8027	0.8027	0.805	0.8035
446A 2	0.0854	0.0911	0.0854	0.0873					
446A 4	0.1442	0.1483	0.1483	0.1469					
446A 5	0.0776	0.0761	0.079	0.0776					

Table A.7: Duration of the Peak of the N1 Call. Data taken for the duration of the peak of the call for all N1 calls. The duration of this peak in frequency was calculated three separate times, and then an average was found.

Duration of the First Section of the Call									
N7 Call	Section Duration	Section Duration	Section Duration	Avg Section Duration (s)	N7/noise Call	Section Duration	Section Duration	Section Duration	Avg Section Duration (s)
201A 3	0.4243	0.4181	0.4243	0.4222	205B 7.1	0.2462	0.2495	0.2365	0.2441
201A 4	0.3886	0.377	0.3863	0.3840	205B 7.2	0.2365	0.2268	0.2268	0.2300
145A 6	0.2542	0.2554	0.2554	0.255	205B 8	0.2978	0.2954	0.2857	0.2930
145A 5	0.1698	0.1641	0.1717	0.1685	205B 9	0.4945	0.4972	0.4945	0.4954
145A 7	0.2485	0.2485	0.2485	0.2485	250B 4	0.2877	0.2877	0.2877	0.2877
201A 5	0.3536	0.3556	0.3536	0.3543	250B 6	0.3337	0.3397	0.3297	0.3344
201A 9	0.2545	0.2418	0.2382	0.2448	250B 7	0.2647	0.2565	0.2298	0.2503
201A 10	0.2901	0.2827	0.2901	0.2876	250B 8	0.2542	0.2519	0.2519	0.2527
					250B 10	0.3201	0.3246	0.3246	0.3231
					241A 1	0.2797	0.2757	0.2777	0.2777

Table A.8: Duration of the First Section of the Call. Data for the duration of the first section of the call for all N7 calls. The duration of this first frictative section of the call was calculated three times, and an average was taken of the three durations.

N4 Call			
Tape and Call Number	Signal Mean Intensity (dB)	Noise Mean Intensity (dB)	Signal to Noise Ratio (dB)
259A 3	1.2818	-18.8705	20.1523
258B 4	-0.8554	-8.9666	8.1112
258B 3	1.9589	-10.3958	12.3547
146A 20	7.1544	-18.6355	25.7899
146A 15	4.0280	-17.3081	21.3361
145A 9	16.7599	-13.8519	30.6118
145A 8	19.3178	-10.2929	29.6107
201A 6	0.4091	-22.1795	22.5886
145A 10	17.2048	-14.4676	31.6724
145A 13	18.2757	-9.1601	27.4358
145A 3	11.1877	-10.1035	21.2912
145A 2	14.2902	-13.9829	28.2731
146A 13	1.4083	-16.4647	17.8730
146A 9	5.3083	-17.1947	22.5030
146A 7	6.4437	-16.6560	23.0997
146A 5	1.6132	-19.1291	20.7423
146A 3	-0.3695	-19.2984	18.9289
146A 2	-2.0508	-19.8659	17.8151
215A 8	-23.4627	-33.7851	10.3224
215A 4	-26.7966	-37.5541	10.7575
215A 2	-20.6254	-35.8291	15.2037
201A 2	5.8270	-20.7066	26.5336
201A 3	-0.1871	-22.3723	22.1852
146A 14	2.9616	-17.6456	20.6072
Average	*2.5451*	*-18.5299*	*21.0750*

Table A.9: Signal and Ambient Levels and SNR for N4 Call. Data on the average intensity levels (dB) for the N4 calls without noise. Average intensity levels were calculated for the first harmonic of each call (signal mean intensity) and the ambient noise of each call (noise mean intensity). From these the signal to noise ratio was calculated.

N4 Call with Noise

Tape and Call Number	Signal Mean Intensity (dB)	Noise Mean Intensity (dB)	Signal to Noise Ratio (dB)
250B 1	12.3297	-7.3951	19.7248
490A 5	10.5020	-3.5395	14.0415
490A 4	3.3834	-8.8142	12.1976
490A 3	2.4215	-9.9788	12.4003
255A 2	-4.8265	-23.3594	18.5392
490A 1	2.0981	-10.7074	12.8055
215A 14	-5.8147	-31.5389	25.7242
215A 13	-15.5014	-32.2801	16.7787
215A 12	-13.2223	-28.8037	15.5814
205B 13	2.3243	-16.1932	18.5175
205B 12	4.1867	-16.1951	20.3818
205B 11	3.7417	-13.3457	17.0874
205B 10	8.0705	-11.1321	19.2026
257B 3	-4.1835	-17.5097	13.3262
146A 1	4.0401	-17.1289	21.1690
250B 3	15.8840	-1.2936	17.1776
250B 5	15.1893	-5.9161	21.1054
214B 8	8.5057	-10.9979	19.5036
214B 9	7.7330	-14.4731	22.2061
146A 16	3.9486	-10.5180	14.4666
146A 19	16.8681	-5.6801	22.5482
355B 9	16.4836	-7.4638	23.9474
258A 1	-1.1397	-16.7020	15.5623
258A 2	-11.3853	-26.1292	14.7439
255A 1	-9.4467	-23.1242	13.6775
490A 2	-0.4470	-10.0478	9.6008
256B 2	-0.9724	-15.5066	14.5342
257B 1	4.7510	-14.1244	18.8754
257B 2	-1.2537	-12.9485	11.6948
250B 2	15.6881	-4.0358	19.7239
214B 4	1.6816	-14.5352	16.2168
205B 6	2.9310	-15.8344	18.7654
205B 4	9.9961	-11.1131	21.1092
205B 5	9.0213	-11.8459	20.8672
Average	*3.3408*	*-14.1239*	*17.4646*

Table A.10: Signal and Ambient Levels and SNR for N4 Call with Noise. Data on the average intensity levels (dB) for the N4 calls with noise. Average intensity levels were calculated for the first harmonic of each call (signal mean intensity) and the ambient noise of each call (noise mean intensity). From these the signal to noise ratio was calculated.

N5 Call

Tape and Call Number	Signal Mean Intensity (dB)	Noise Mean Intensity (dB)	Signal to Noise Ratio (dB)
146A 10	22.9089	-16.1260	39.0349
490B 4	8.3919	-19.3849	27.7768
214A 1	-9.4213	-26.4456	17.0243
145A 18	10.4388	-13.2442	23.6830
145A 17	6.3737	-16.2707	22.6444
145A 16	4.6083	-14.0131	18.6214
145A 15	18.9162	-6.1669	25.0831
145A 14	9.2765	-9.8261	19.1026
215A 3	-22.6835	-35.3507	12.6672
214B 11	11.3486	-17.3661	28.7147
215A 5	-14.3108	-34.1050	19.7942
214B 10	7.5141	-13.0347	20.5488
215A 6	-20.0958	-36.7512	16.6554
259A 2	-3.7833	-22.0997	18.3164
146A 11	12.2220	-8.9199	21.1419
259A 1	3.6563	-18.8275	22.4838
145A 1	19.8850	-12.5784	32.4634
258B 6	5.4003	-10.1053	15.5056
258B 5	5.9153	-13.6431	19.5584
201A 13	-11.8767	-28.0477	16.1710
201A 12	-5.8086	-27.5884	21.7798
201A 11	0.5183	-27.1774	27.6957
145A 4	9.0434	-12.6489	21.6923
Average	*2.9755*	*-19.1183*	*22.0983*

Table A.11: Signal and Ambient Levels and SNR for N5 Call. Data on the average intensity levels (dB) for the N5 calls without noise. Average intensity levels were calculated for the first harmonic of each call (signal mean intensity) and the ambient noise of each call (noise mean intensity). From these the signal to noise ratio was calculated.

N5 Call with Noise			
Tape and Call Number	Signal Mean Intensity (dB)	Noise Mean Intensity (dB)	Signal to Noise Ratio (dB)
492A 1	9.2998	-2.8873	12.1871
490B 3	-0.9273	-15.8596	14.9323
490B 2	-0.3464	-12.9573	12.6109
490B 1	-5.0862	-13.1106	8.0244
241B 3	-0.8201	-15.7817	14.9616
241B 2	-9.9357	-14.0387	4.1030
205A 1	10.9567-0.5586	11.5153	
215A 10	-3.5412	-28.5212	24.9800
205B 2	-0.4506	-10.1857	9.7351
146A 2	3.4452	-9.2465	12.6917
445A 1	20.7871	8.1958	12.5913
255A 3	-10.1442	-26.8525	16.7083
355B 5	12.8596	2.2237	10.6359
355B 4	14.7986	2.8016	11.9970
355B 3	14.3162	-2.0203	16.3365
355B 1	16.3605	-1.2244	17.5849
201A 7	-7.3323	-20.6256	13.2933
146A 18	5.0516	-2.9527	8.0043
146A 17	9.1330	-12.6787	21.8117
214B 7	7.3902	-5.1648	12.5550
214B 6	11.1035	-7.2260	18.3295
250B 13	13.4221	-9.7758	23.1979
250B 12	16.9081	-3.4544	20.3625
250B 9	16.6821	-2.5623	19.2444
214B 3	9.9551	-12.1447	22.0998
214B 1	9.6790	-12.9051	22.5841
241B 4	3.5306	-9.0731	12.6037
Average	*6.1887*	*-8.8365*	*15.0252*

Table A.12: Signal and Ambient Levels and SNR for N5 Call with Noise. Data on the average intensity levels (dB) for the N5 calls with noise. Average intensity levels were calculated for the first harmonic of each call (signal mean intensity) and the ambient noise of each call (noise mean intensity). From these the signal to noise ratio was calculated.

N1 Calls

	Recording periods	Total time (min.)	Call Rate (calls/min)
no boat noise	7	54.92	0.882
boat noise	13	161.25	0.748

	Recording periods	Total time (min.)	Call Rate (calls/min)
no boat noise	8	56.53	1.359
boat noise	14	144.82	0.519

N3 Calls

	Recording periods	Total time (min.)	Call Rate (calls/min)
no boat noise	3	12.72	0.942
boat noise	3	42.38	0.104

N4 Calls

	Recording periods	Total time (min.)	Call Rate (calls/min)
no boat noise	11	75.58	3.008
boat noise	21	209.78	1.970

N5 Calls

	Recording periods	Total time (min.)	Call Rate (calls/min)
no boat noise	10	71.58	1.983
boat noise	17	196.03	1.048

N7 Calls

	Recording periods	Total time (min.)	Call Rate (calls/min)
no boat noise	8	57.22	1.777
boat noise	10	78.78	0.908

N8 Calls

	Recording periods	Total time (min.)	Call Rate (calls/min)
no boat noise	5	47.58	0.396
boat noise	3	29.68	0.633

N9 Calls

	Recording periods	Total time (min.)	Call Rate (calls/min)
no boat noise	11	75.58	2.451
boat noise	19	202.45	1.841

N12 Calls

	Recording periods	Total time (min.)	Call Rate (calls/min)
no boat noise	4	19.60	0.798
boat noise	3	16.85	0.572

N43 Calls

	Recording periods	Total time (min.)	Call Rate (calls/min)
no boat noise	4	22.02	0.268
boat noise	2	37.17	0.228

N47 Calls

	Recording periods	Total time (min.)	Call Rate (calls/min)
no boat noise	1	6.18	0.162
boat noise	0	0.00	0.00

Other Calls

	Recording periods	Total time (min.)	Call Rate (calls/min)
no boat noise	2	13.52	0.366
boat noise	4	61.73	0.098

Total Calls

	Recording periods	Total time (min.)	Call Rate (calls/min)
no boat noise	11	75.58	10.982
boat noise	21	209.78	5.817

Table A.13: Average Call Rates. The average call rate of each call type and for the total calls with and without boat noise.

Appendix B

Figures of Boxplots and Histograms

The figures include all the individual boxplots and histograms for the different spectral characteristics of the calls examined. Figures B.1, B.2, B.3, and B.4 show the boxplots for all spectral characteristics examined for the N4 call. Figures B.5, B.6, and B.7 show boxplots for all spectral characteristics examined for the N5 call. Figures B.8, B.9, B.10, and B.11 show the boxplots for all spectral characteristics examined for the N1 call. Figures B.12, B.13, B.14, and B.15 show the boxplots for all spectral characteristics examined for the N7 call. Figure B.16 and Figure B.17 show the histograms for the characteristics compared with and without boat noise for the N4 call. Figure B.18 and Figure B.19 show the histograms for the characteristics compared for the N5 call.

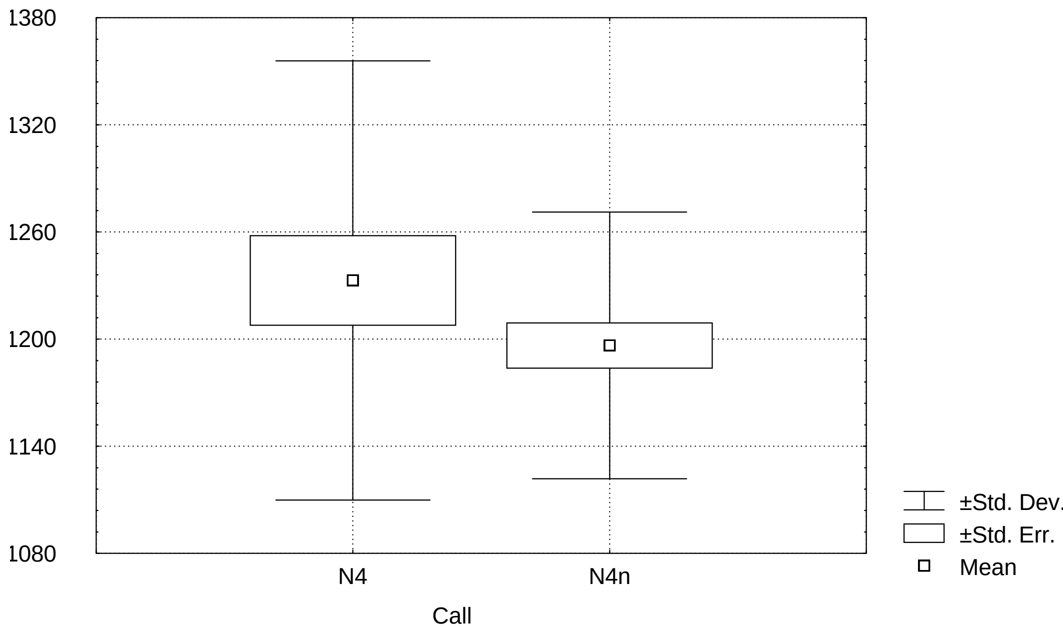

Figure B.1: Boxplot: N4 Call Average Frequency. One of four sets of boxplots for the spectral characteristics of the N4 call without and with noise. This set of boxplots is for the average frequency of the first harmonic of the N4 call without and with noise.

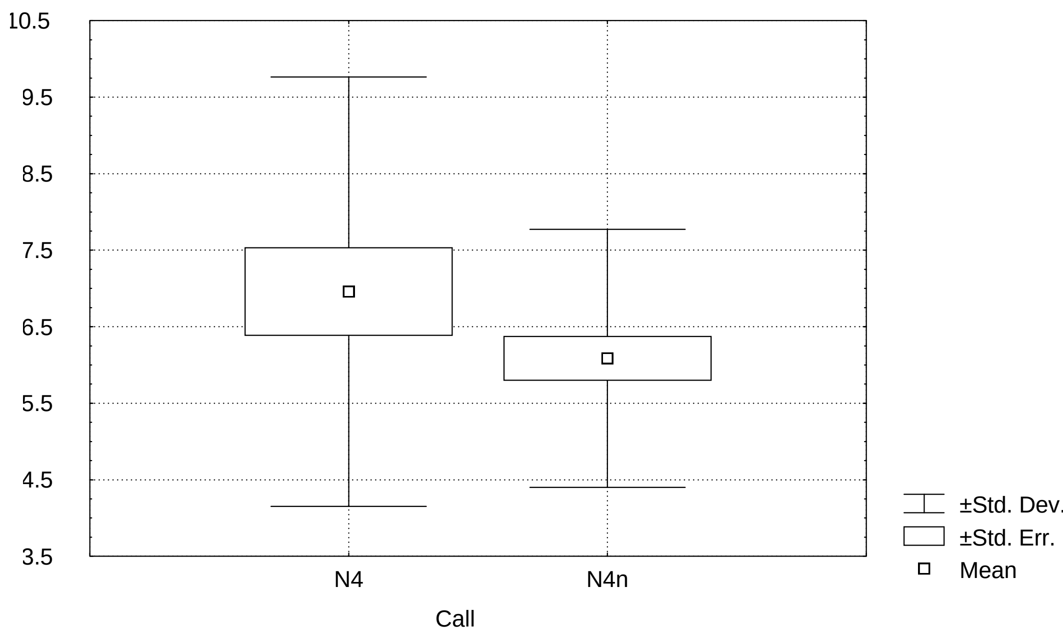

Figure B.2: Boxplot: N4 Call Harmonics. One of four sets of boxplots for the spectral characteristics of the N4 call without and with noise. This set of boxplots is for the number of harmonics in the N4 call without and with boat noise.

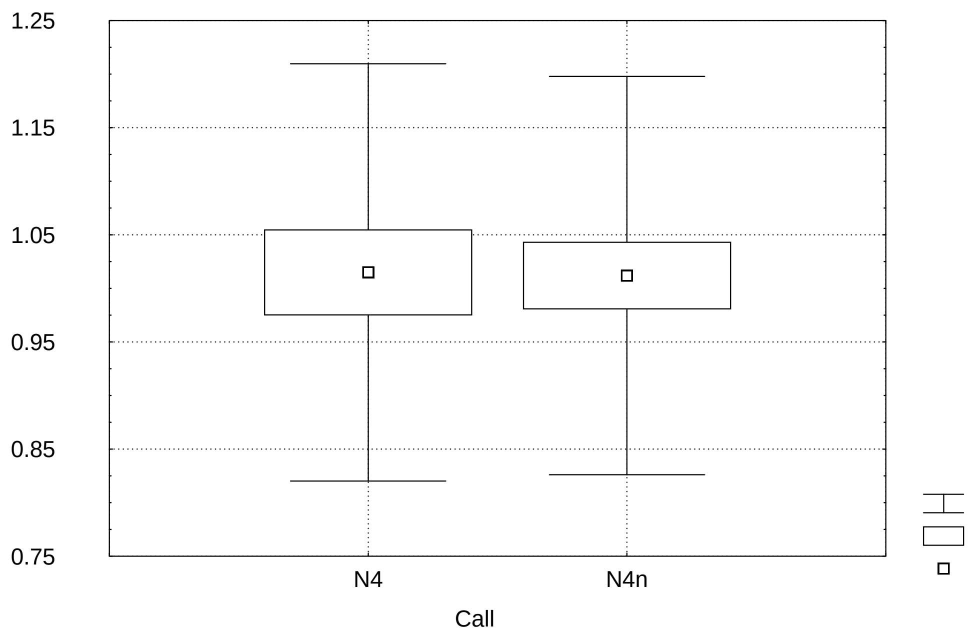

Figure B.3: Boxplot: N4 Call Duration. One of four sets of boxplots for the spectral characteristics of the N4 call without and with noise. This set of boxplots is for the duration of the N4 call without and with boat noise.

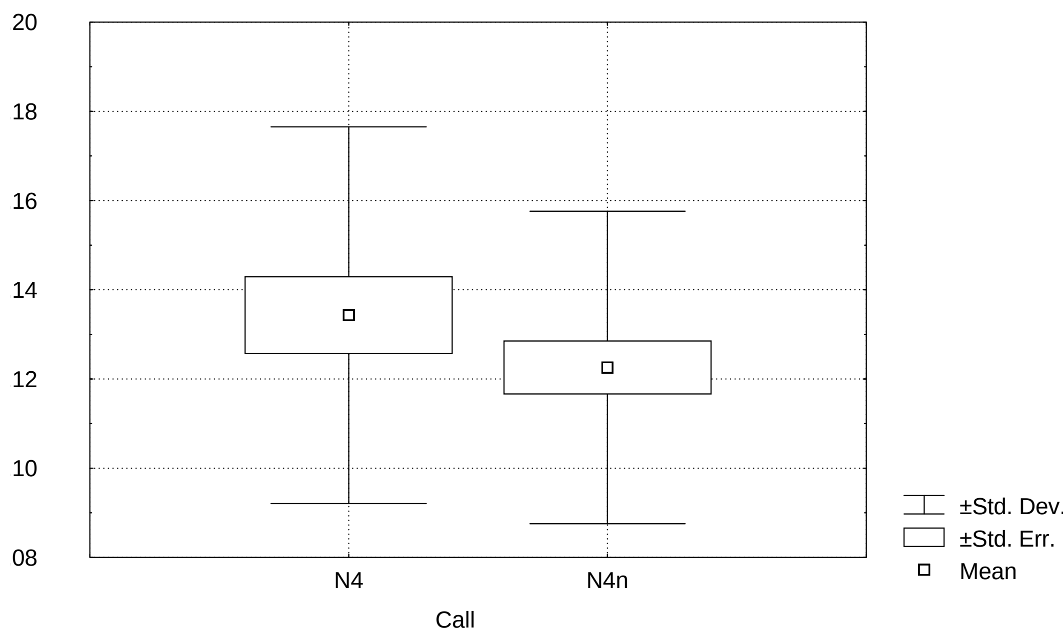

Figure B.4: Boxplot: N4 Call Peak Duration. One of four sets of boxplots for the spectral characteristics of the N4 call without and with noise. This set of boxplots is for the duration of the frequency peak in the N4 call without and with boat noise.

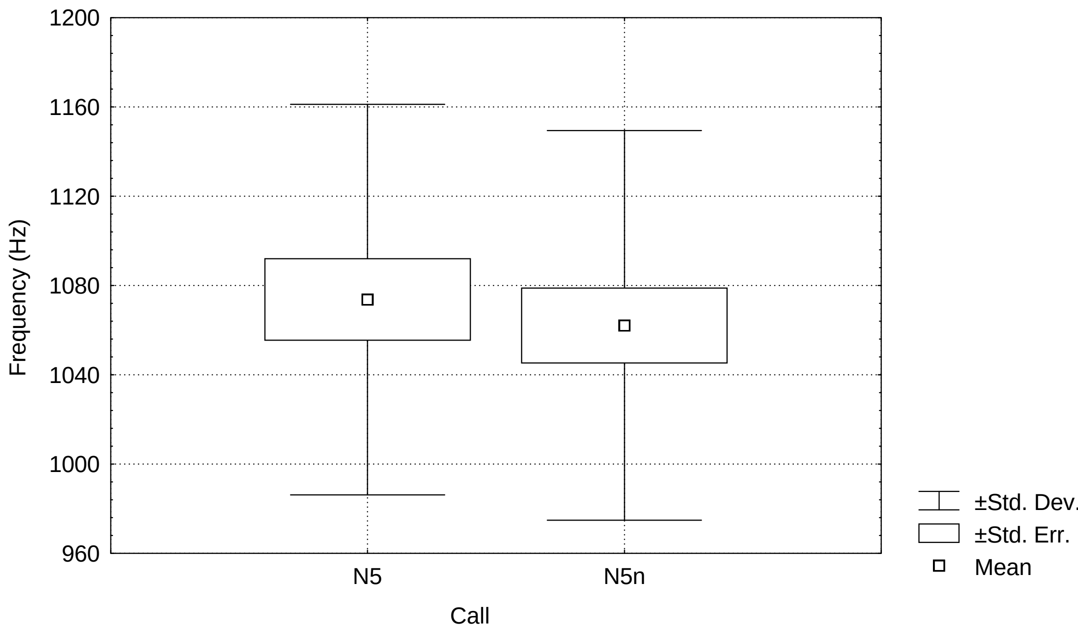

Figure B.5: Boxplot: N5 Call Average Frequency. One of three sets of boxplots for the spectral characteristics of the N5 call without and with noise. This set of boxplots is for the average frequency of the first harmonic of the N5 call without and with noise.

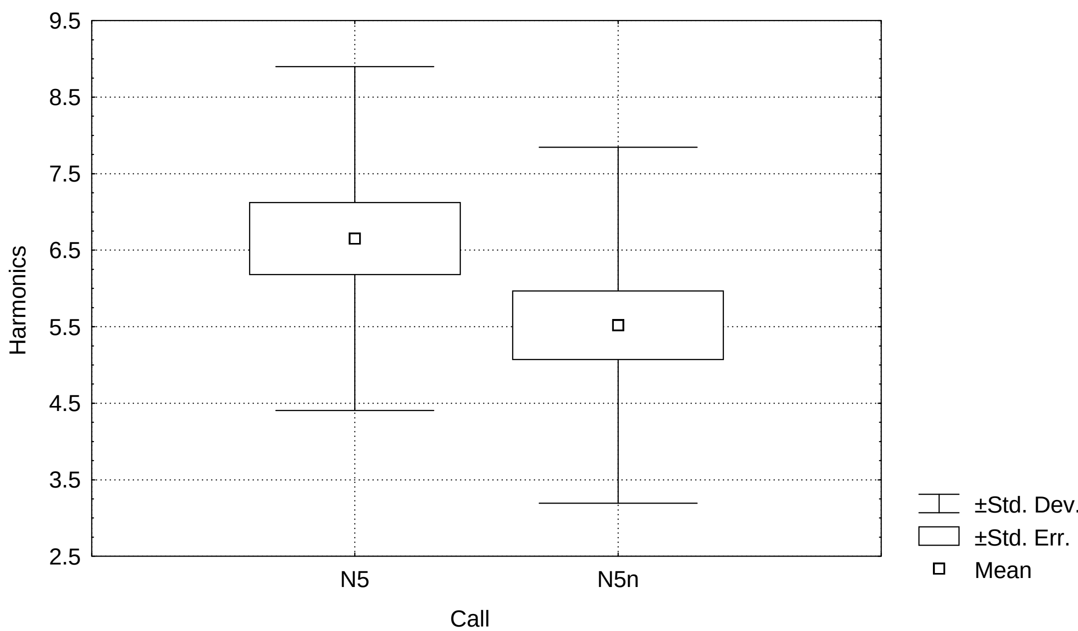

Figure B.6: Boxplot: N5 Call Harmonics. One of three sets of boxplots for the spectral characteristics of the N5 call without and with noise. This set of boxplots is for the number of harmonics in the N5 call without and with boat noise.

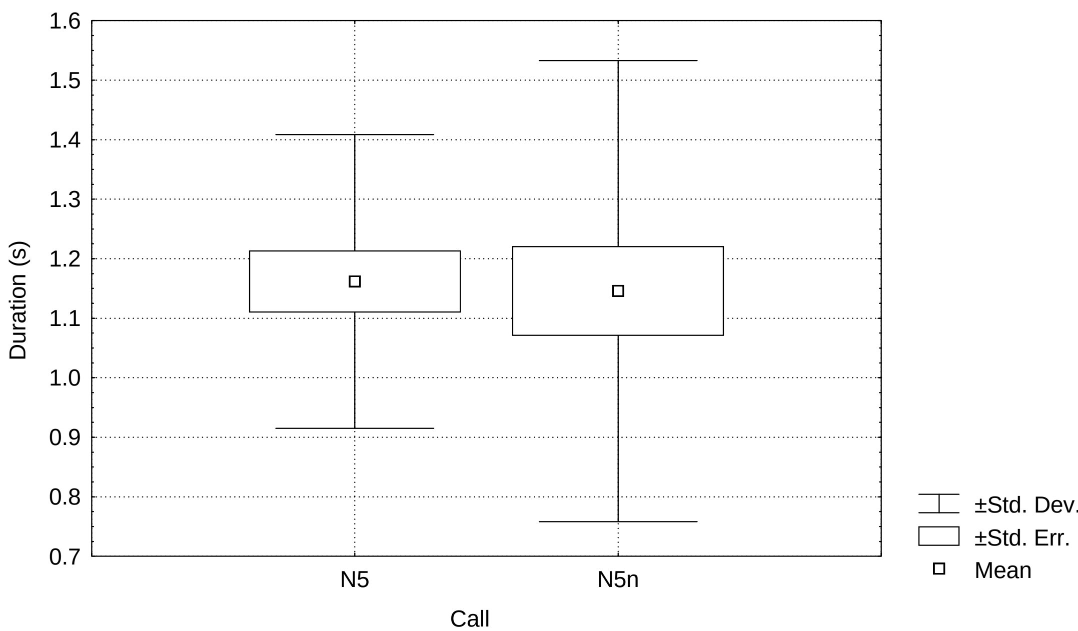

Figure B.7: Boxplot: N5 Call Duration. One of three sets of boxplots for the spectral characteristics of the N5 call without and with noise. This set of boxplots is for the duration of the N5 call without and with boat noise.

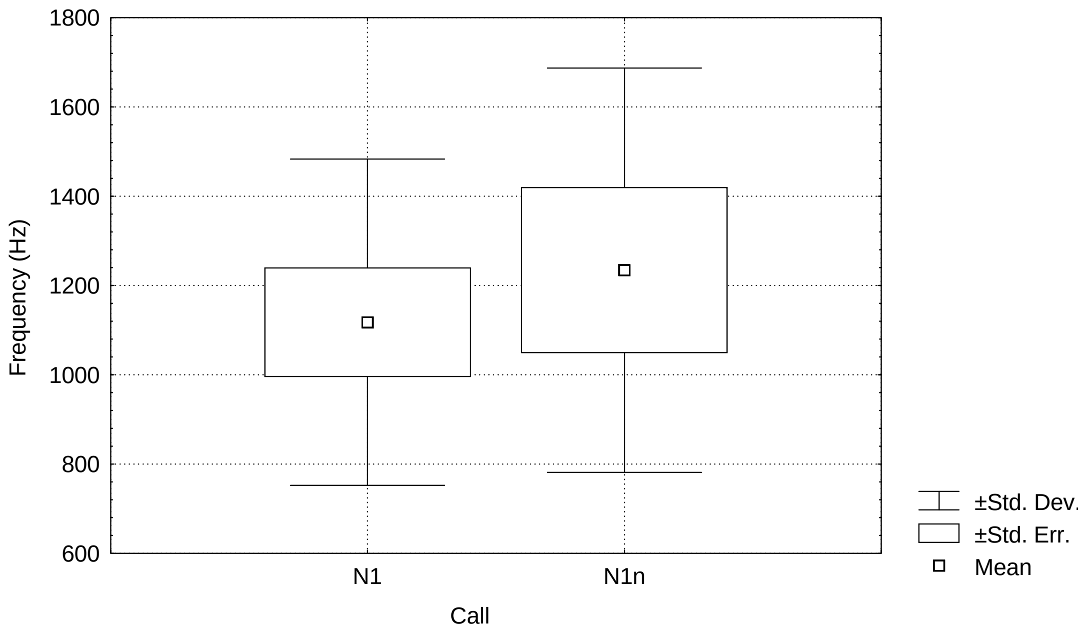

Figure B.8: Boxplot: N1 Call Average Frequency. One of four sets of boxplots for the spectral characteristics of the N1 call without and with noise. This set of boxplots is for the average frequency of the first harmonic of the N1 call without and with noise.

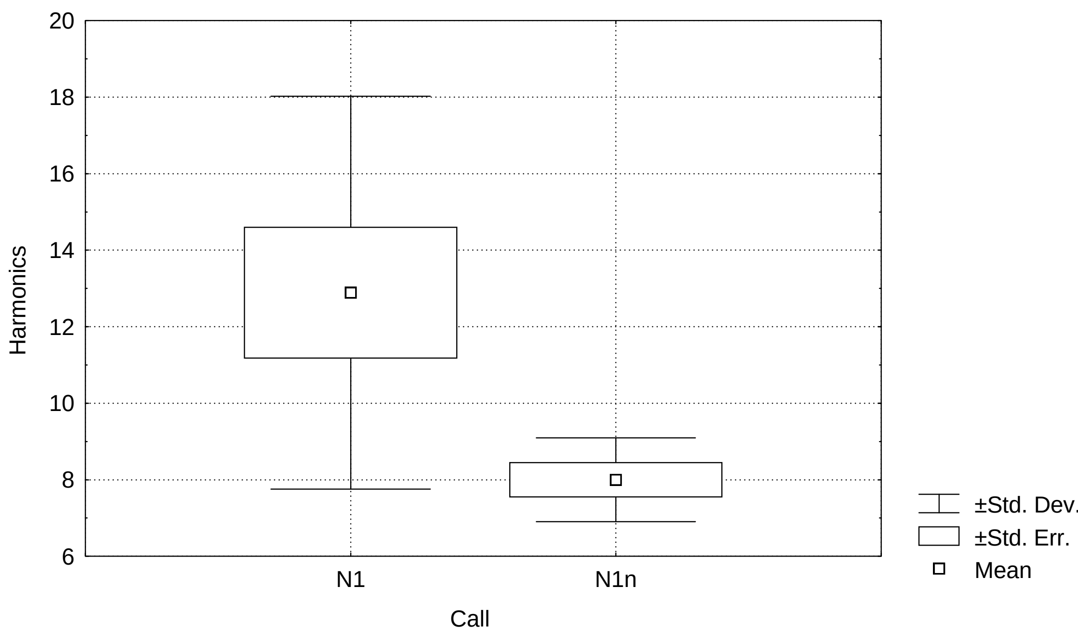

Figure B.9: Boxplot: N1 Call Harmonics. One of four sets of boxplots for the spectral characteristics of the N1 call without and with noise. This set of boxplots is for the number of harmonics in the N1 call without and with boat noise.

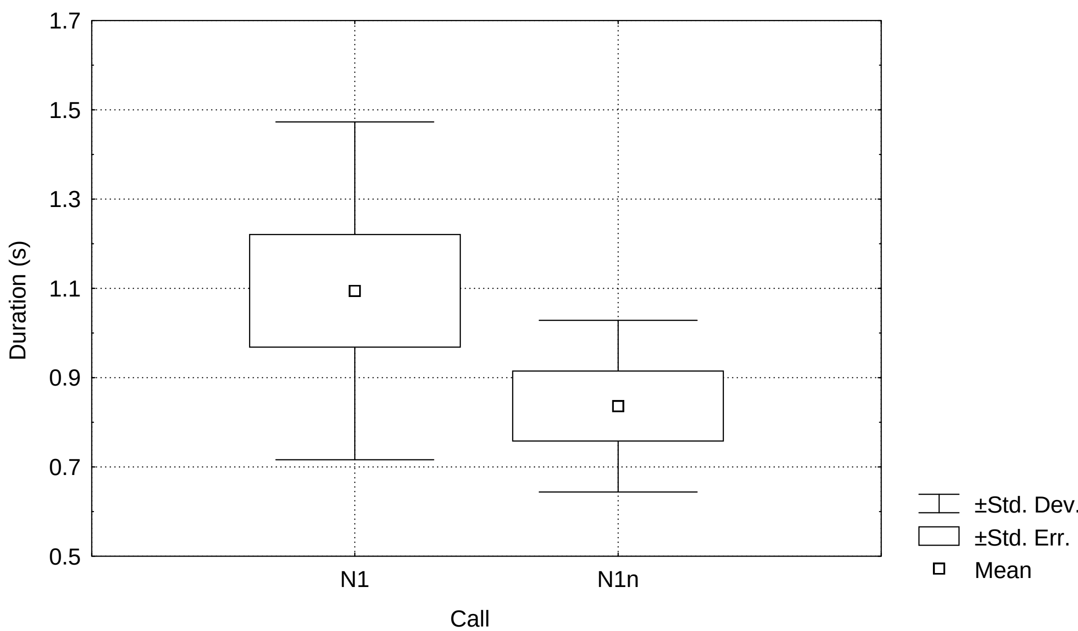

Figure B.10: Boxplot: N1 Call Duration. One of four sets of boxplots for the spectral characteristics of the N1 call without and with noise. This set of boxplots is for the duration of the N1 call without and with boat noise.

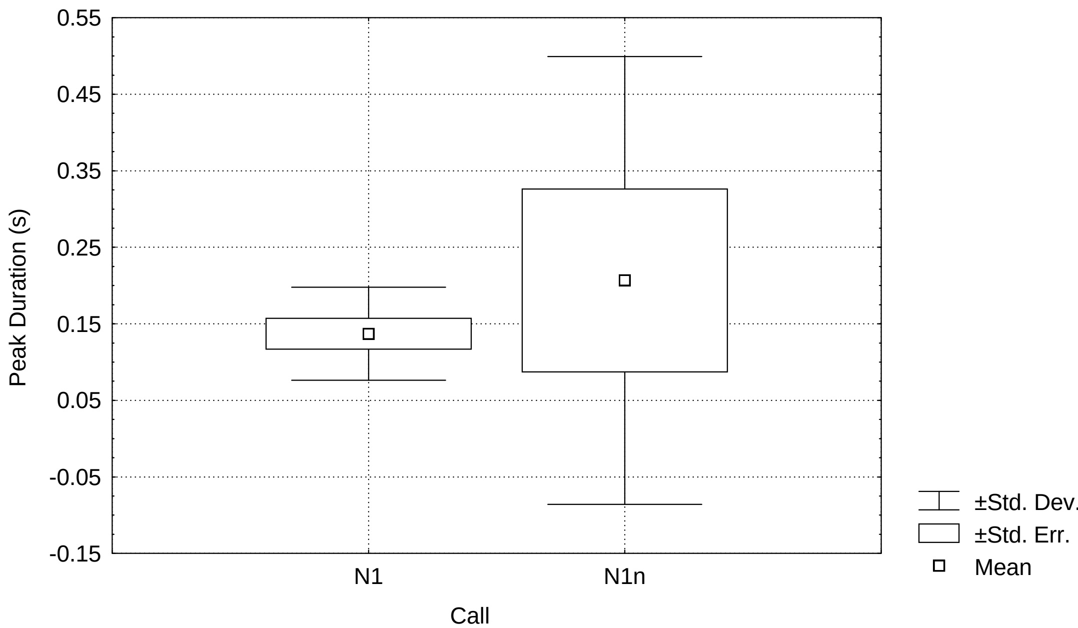

Figure B.11: Boxplot: N1 Call Peak Duration. One of four sets of boxplots for the spectral characteristics of the N1 call without and with noise. This set of boxplots is for the duration of the frequency peak in the N1 call without and with boat noise.

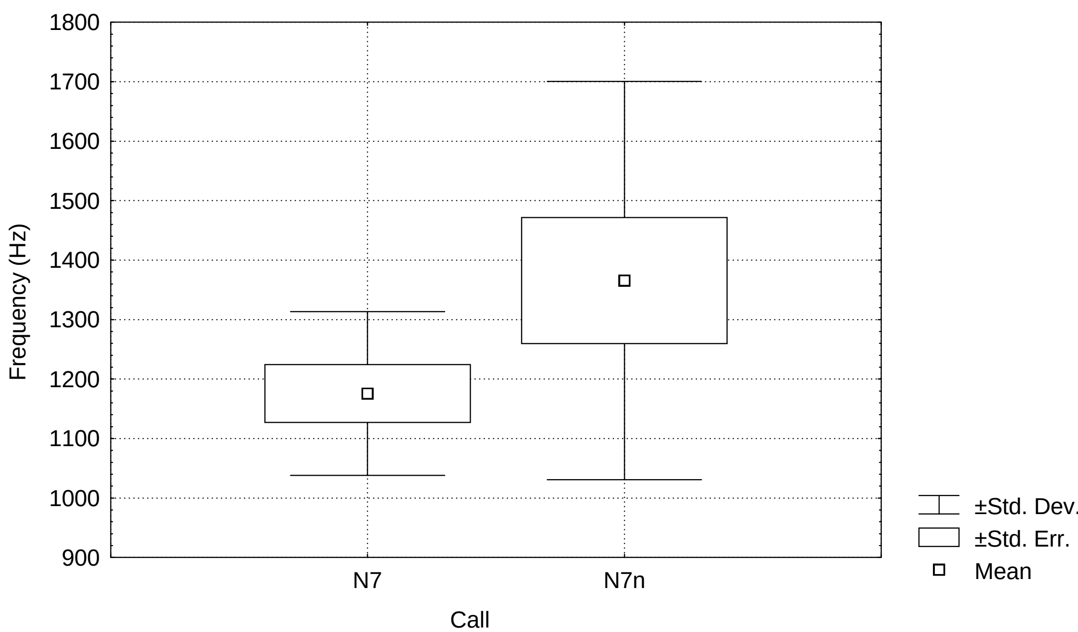

Figure B.12: Boxplot: N7 Call Average Frequency. One of four sets of boxplots for the spectral characteristics of the N7 call without and with noise. This set boxplots is for the average frequency of the first harmonic of the N7 call without and with noise.

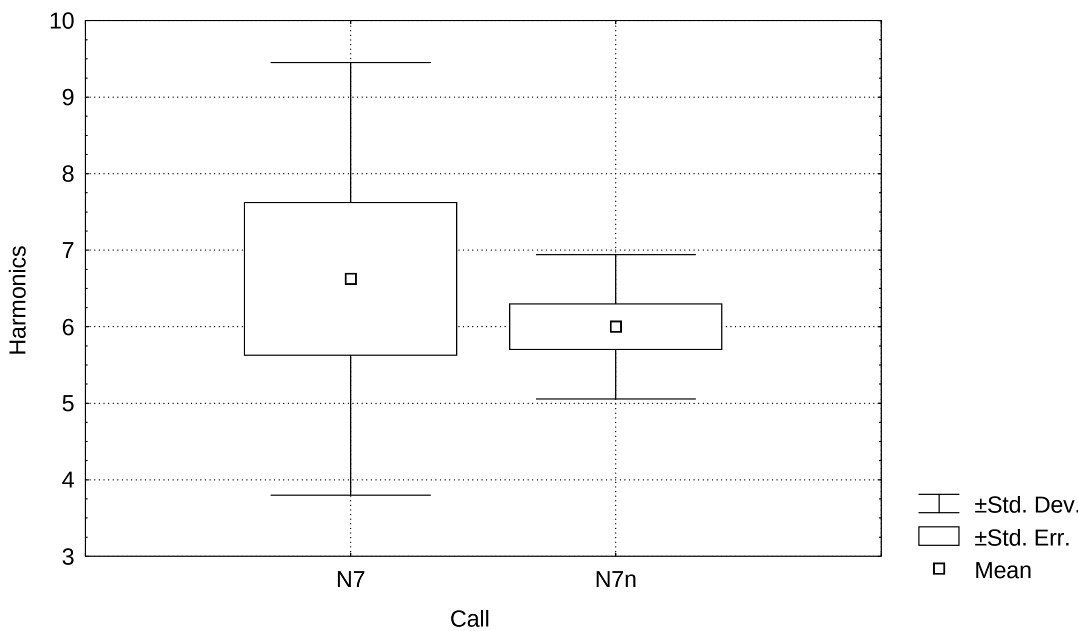

Figure B.13: Boxplot: N7 Call Harmonics. One of four sets of boxplots for the spectral characteristics of the N7 call without and with noise. This set of boxplots is for the number of harmonics in the N7 call without and with boat noise.

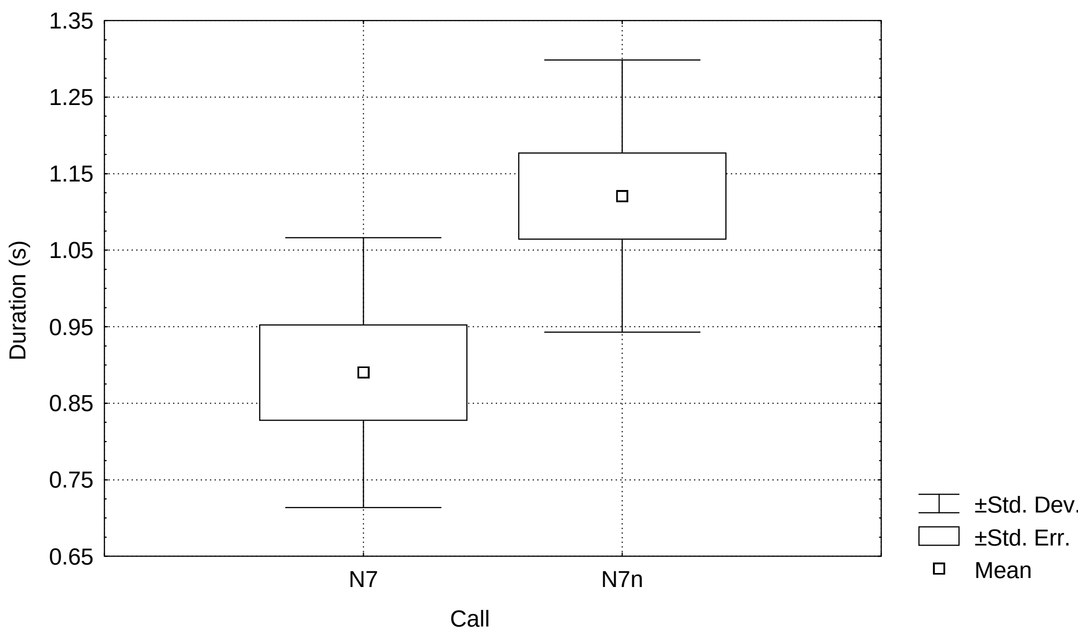

Figure B.14: Boxplot: N7 Call Duration. One of four sets of boxplots for the spectral characteristics of the N7 call without and with noise. This set of boxplots is for the duration of the N7 call without and with boat noise.

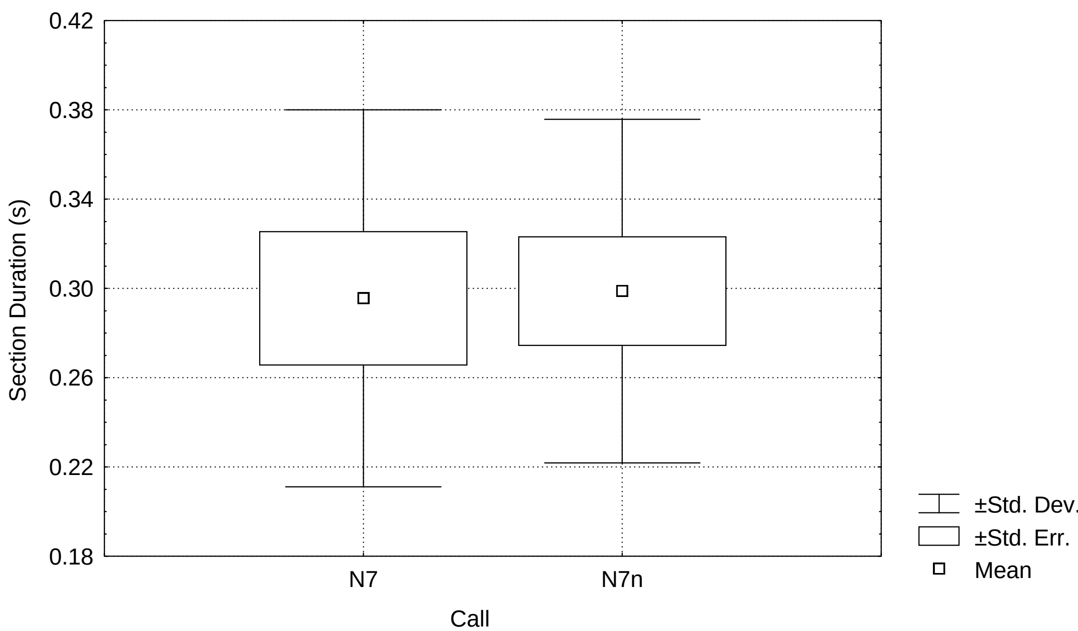

Figure B.15: Boxplot: N7 Call Section Duration. One of four sets of boxplots for the spectral characteristics of the N7 call without and with noise. This set of boxplots is for the duration of the first section of the call without and with boat noise.

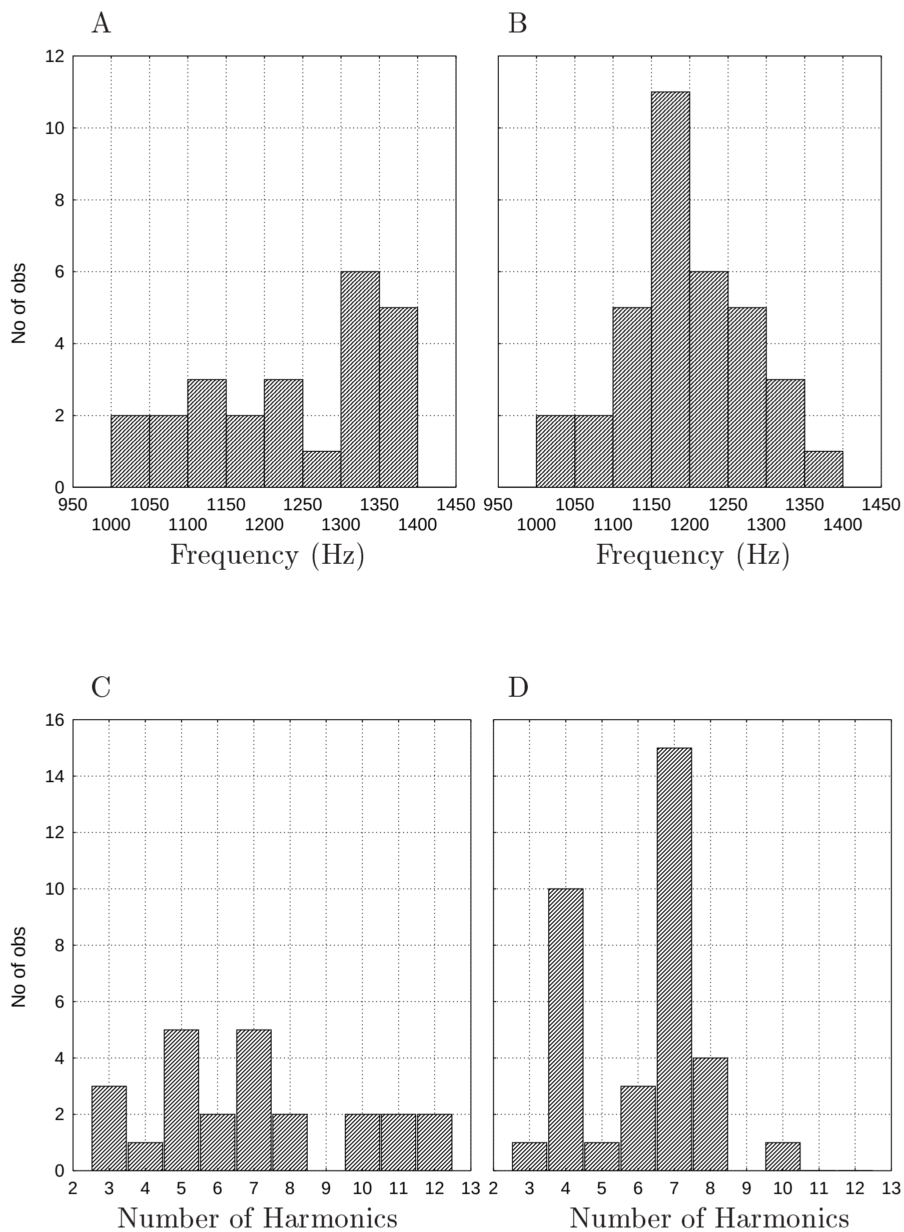

Figure B.16: Histograms for the average frequency and number of harmonics of the N4 call with and without noise. Figure A shows the histogram for the average frequency of the first harmonic of the N4 call without boat noise, and Figure B shows the histogram for the average frequency of the first harmonic of the N4 call with boat noise. Figure C shows the histogram for the number of harmonics of the N4 call without boat noise, and Figure D shows the histogram for the number of harmonics of the N4 call with boat noise.

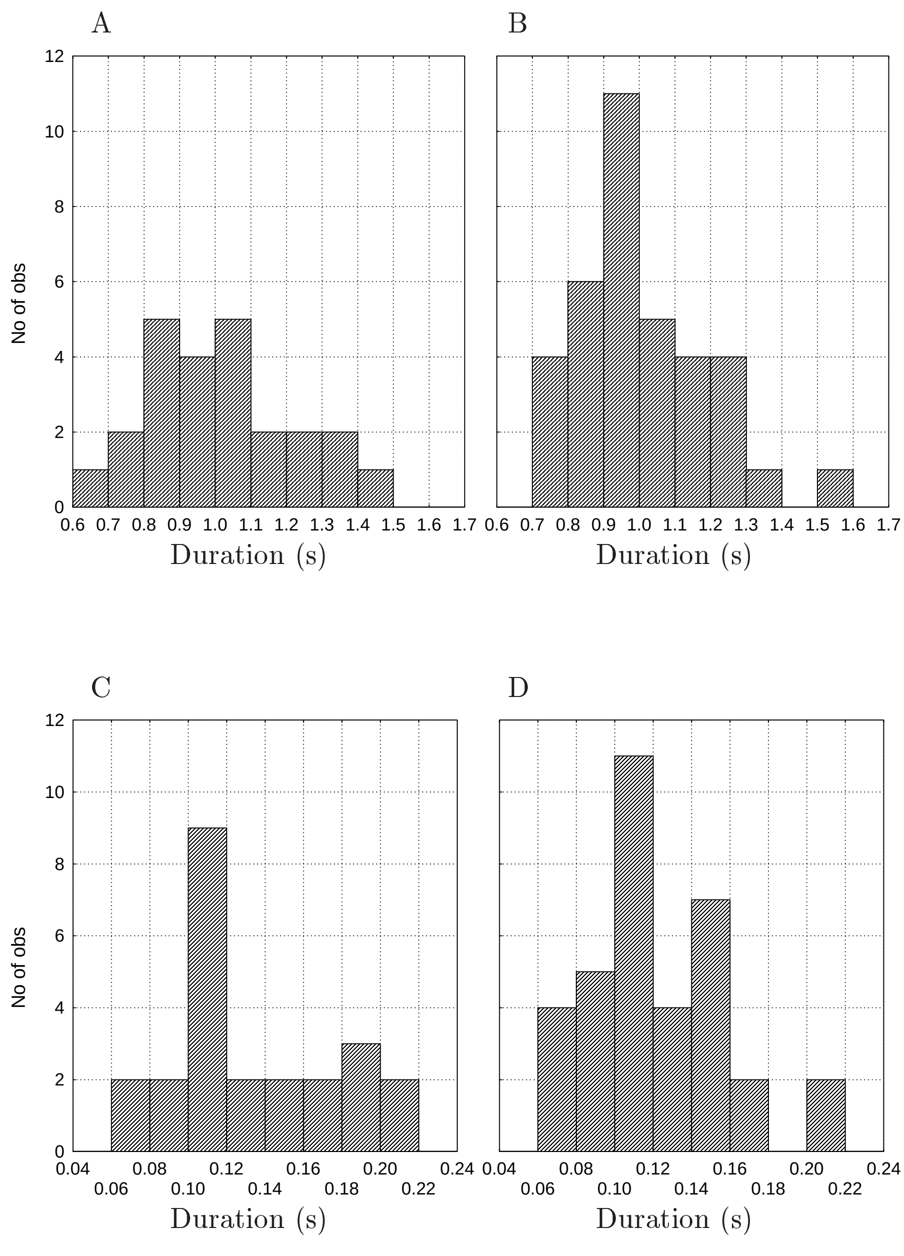

Figure B.17: Histograms for the duration and peak duration of the N4 call with and without noise. Figure A shows the histogram for the duration of the N4 call without boat noise, and Figure B shows the histogram for the duration of the N4 call with boat noise. Figure C shows the histogram for the duration of the peak in frequency of the N4 call without boat noise, and Figure D shows the histogram for the duration of the peak in frequency of the N4 call with boat noise.

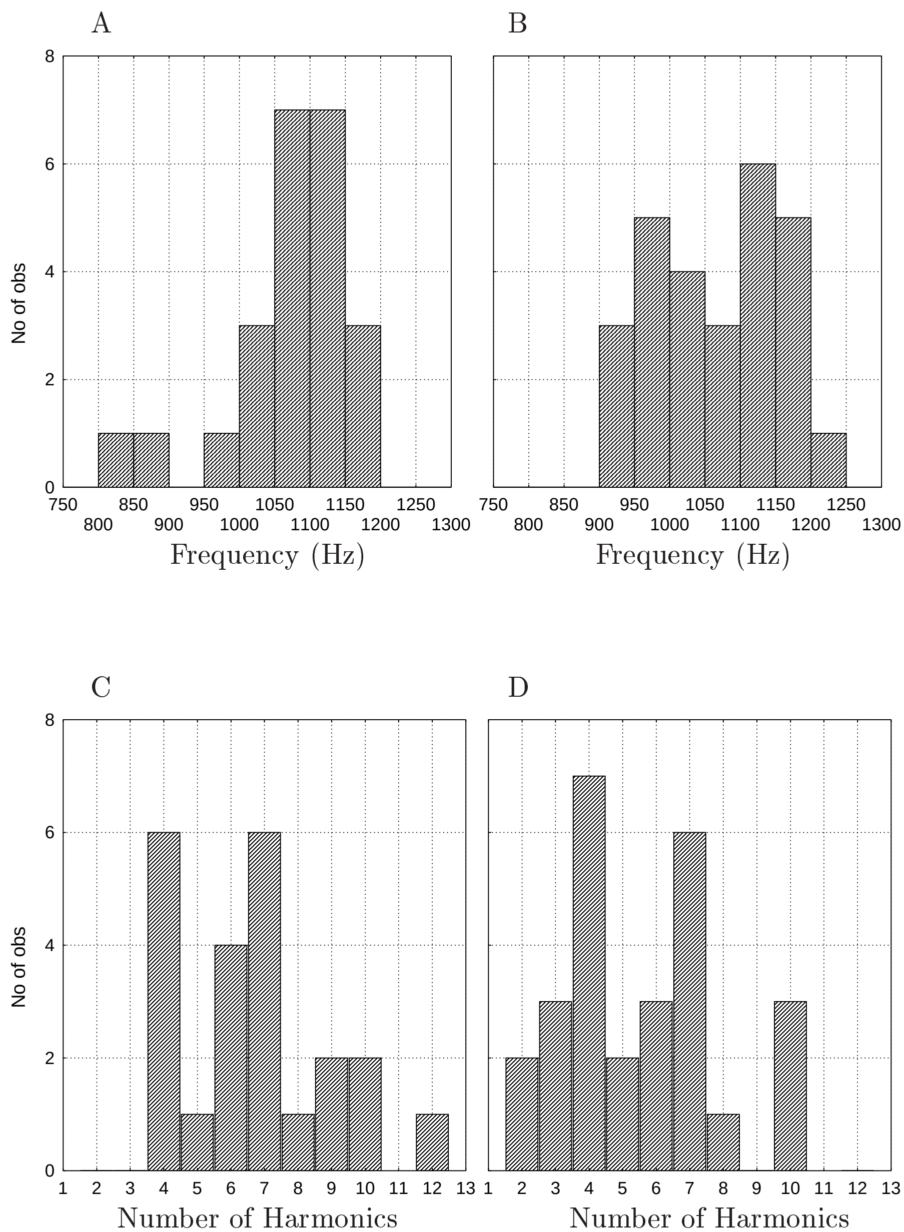

Figure B.18: Histograms for the average frequency and number of harmonics of the N5 call with and without noise. Figure A shows the histogram for the average frequency of the first harmonic of the N5 call without boat noise, and Figure B shows the histogram for the average frequency of the first harmonic of the N5 call with boat noise. Figure C shows the histogram for the number of harmonics of the N5 call without boat noise, and Figure D shows the histogram for the number of harmonics of the N5 call with boat noise.

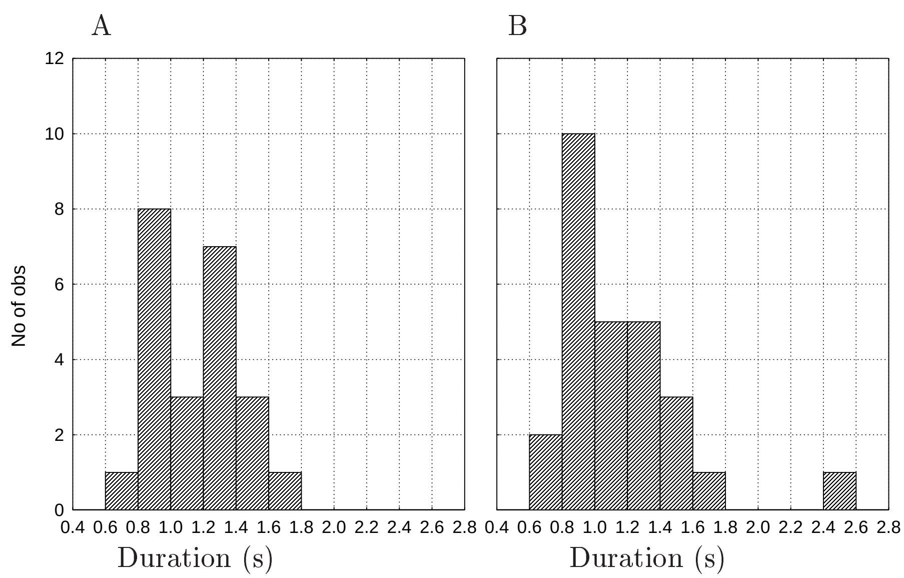

Figure B.19: Histograms for the duration of the N5 call with and without noise. Figure A shows the histogram of the duration of the N5 call without boat noise, and Figure B shows the histogram of the duration of the N5 call with boat noise.