Masking avoidance by Southern Resident Killer Whales in response to anthropogenic sound.

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Introduction

Southern resident killer whales (SRKWs or southern residents) are the population of *Orcinus orca* that reside in the inland waters of Vancouver Island and Washington state from late spring through the fall (Ford et al. 2000). Their range extends from the coastal waters of central California to north of Vancouver Island and around the Queen Charlotte Islands (Wiles 2004). The SRKW population is comprised of J, K, and L pods which, when congregating together are referred to as a superpod. Each pod is highly structured and shows a stable organization around matrilines (Ford et al. 2000). A decline in the SRKW population was marked by the capture or death of 55 killer whales for the aquarium trade from 1965 to 1978 (Bigg et al. 1987). Under the Endangered Species Act, the SRKWs were listed as endangered in December of 2005 and the required recovery plan summarizes numerous threats that could contribute to the decline of southern residents and impede their recovery (NMFS 2006). One such threat is the presence of anthropogenic underwater sound, which could mask vocal communication (Richardson et al. 1995). Although vessel noise could impede vocal communication it has not yet been shown to do so.

As highly social animals, communication is vital to killer whale interactions from the individual to the superpod level. In marine environments auditory communication is often more important than olfactory or visual communication. Chemicals that can be sensed with taste or in an olfactory manner depend on currents for dispersal through the water so are not reliable as omnidirectional signals (Nicol 1967). These senses are developed in many marine mammals but in order for them to serve in communication orcas would need organs for production of the chemical as well as chemoreception (Nicol 1967). Visual sensing is limited because of rapid light attenuation with depth. Both due to the scattering of light by water molecules and the absorptive properties of particulates the intensity of light is decreased greatly as it moves deeper into the water column from the surface (Nicol 1967). Penetration of light is greatest in the open ocean but killer whales are feeding in near-shore waters where turbidity increases the absorption of light (Utterback 1936). Auditory communication is most successful in the marine environment as sound travels well and for long distances in water (Nicol 1967). It is evidenced by the use of highly advanced vocalizations during numerous behaviors that orcas rely on their auditory sense for a large portion of their communication (Ford et al. 2000, Miller 2002).

There are three types of killer whale vocalizations: clicks (which are used in echolocation), whistles, and discrete calls. Pods have differing dialects made up of specific numbers, types, and repetitions of discrete call types (Ford 1991). Discrete calls are the most frequent vocalizations. Pods typically have one primary call that accounts for more than 52% of all discrete calls produced (Hoelzel and Ozborne 1986). The majority of their discrete calls occur within the amplitude range of 105 and 124 dB re 1µ Pa (Erbe 2002). Threshold audiograms for killer whales show that they are most sensitive at frequencies near 20 kHz and their discrete calls have a fundamental frequency of around 1 - 10 kHz (Ford 1987, Szymanski et al. 1999). These discrete vocalizations are thought to be important in maintaining group cohesion, as well as foraging and coordination of group movement (Foote 2005, Miller 2002).

During the summer months, the SRKW frequently inhabit the Haro Strait where there is a regular presence of large tankers and container ships as a result of it serving as a major shipping lane for both the U.S. and Canada. Other large vessels frequently present in the vicinity of the southern residents include ferries that service residents and visitors of the islands and military ships for both the U.S. and Canada. Numerous personal vessels are often on the water for recreation as well as transportation needs throughout the numerous islands. The SRKW themselves are a popular recreation attraction drawing not only personal vessels but also whale watching tour boats into close proximity. The number of these boats has increased to an average of 22 vessels accompanying orcas for the majority of daylight hours (Foote 2004, Koski 2006). All of these vessels create anthropogenic sound, which increases the background levels present in the SRKW environment.

During situations of elevated background sound caused by vessel traffic, SRKW vocalizations have the potential to be masked. In order to maintain communication, the effects of masking must be overcome. This can be achieved by increasing duration, increasing amplitude, or changing the frequency of the calls to be outside the range of the interfering sound (Heil and Neubauer 2003, Erbe 2002, Foote 2004). Increased signal duration has been shown to increase the perception threshold of some Odontecetes (Johnson 1967). For killer whales in particular, Foote (2004) showed increased duration of vocalizations in the presence of vessel traffic. Determining a change in amplitude has been limited by a lack of ability to determine the distance from the receiver to the source of the call.

In the open ocean compared to inshore environments there is a higher level of natural background sound due to greater wave and wind effects. Off shore populations of killer whales over evolutionary time scales have developed higher average minimum and maximum frequencies of calls than SRKWs (Foote 2004). Since the increase in vessel traffic in the habitat of the SRKW has occurred most notably in the past decade, the changes in this population would be ontogenetic, but could feasibly follow a similar path as the offshore population (Rabine and Green 2002). Alterations of frequency to avoid masking have also not been investigated, likely because it is more complicated. Frequency (pitch) of discrete calls varies between call types and may also vary during different behaviors (Morton 1977). In order to determine changes in frequency in the presence of vessel sound, group behavior must be controlled for.

The purpose of this study is to determine if orcas alter their vocalizations in response to the level of anthropogenic sound in their environment. To this end, the following three hypotheses will be tested while controlling for call type and group behavior:

H_1: Stereotyped call duration will increase as the amplitude of background noise increases.

H_2: The amplitude of stereotyped calls will increase as the amplitude of background noise increases.

H_3: The minimum frequency of stereotyped calls will vary when the predominant noise frequency changes.

Methods

Study of southern resident killer whales was conducted in the waters surrounding the San Juan Islands, Washington, USA, predominantly in Haro Strait (Fig.1). Southern resident killer whale vocalizations were recorded from August 27th to October 20th 2007 while aboard the *Gato Verde,* a 42-foot catamaran sailing vessel. Two electric propulsion motors run from battery banks charged with a bio-diesel generator to power the *Gato Verde*. The propulsion system creates very little underwater noise allowing a hydrophone array to be towed with limited observer interference. When whales of J, K, or L pods were encountered, a four hydrophone array was deployed off the port stern of the *Gato Verde*. The array was a linear arrangement of four Lab-core hydrophones with peak sensitivity of 5,000 Hz (down 30 dB at 200 and 10,500 Hz). Underwater sound was recorded using two solid state recorders with a proprietary link for sample accuracy. The solid state recorders were Sound Devices 702 with a flat frequency response from 10 Hz to 40 kHz (+0.1,-0.5 dB), set at a sampling rate of 44,100 samples per second and 16 bit depth. To limit surface noise, the hydrophone was weighted to an approximate depth of 3 m. The entire recording system was calibrated, so that calculations of amplitude were made in dB re 1 μPa and therefore directly comparable to other studies. During recording periods, the general group behavior of killer whales was recorded as rest, travel, forage, play, or milling following the descriptions in the SRKW Behavior Workshop Final Report (NMFS 2004).

Recordings were imported into Audacity 1.2.4. (Dominic Mazzoni). Each call was isolated as a separate call file and accompanied by a corresponding sound file for analysis of background noise levels. The background noise file was extracted from the sound file just prior to the corresponding killer whale vocalization. Each call file was visually compared with the call catalog to determine call type (Ford 1987). Annotations provided by Kenna Lehmann, who as a portion of her work, identified all calls in all recordings allowed better detection of S1 calls during the separation of sound files and thereby greatly increased sample size. A series of scripts were written, by Jason Wood, in MatLab 7.4 (Mathworks) to automate the analysis of call parameters and noise levels. Duration, amplitude, and minimum frequency were determined and recorded for each call file. Amplitude and predominant noise frequency were determined for each noise file and the duration of noise files was set at the average duration of focal vocalizations. Predominant noise frequency is defined as the mean frequency over the majority of the noise amplitude.

Duration

The length of the call file was determined as the duration of the call, as it was restricted to only include the call when separated in Audacity.

Amplitude

In MatLab, received amplitude level was determined as the broadband RMS amplitude for both call and noise files. Both behavioral changes in killer whale calls due to vessel noise and a change in distance from the source to receiver could affect the received level of amplitude in the recording. Therefore, to elucidate a change due to vessel noise, the source level of a call was determined. Determining the source level of a call from the recorded level was done by determining the distance between the vocalizing killer whale and the receiver and then calculating the loss of amplitude over that distance based on a spherical spreading model (Richardson et al. 1995). The effects of bathymetry were too much to incorporate in this study so equation 1 was used to determine source amplitude levels of killer whale vocalizations, where R is the distance from the vocalizing orca to the hydrophone.

$$\text{Source Level} = \text{Received Level} + 20 \log_{10} R \qquad \text{Eq. 1}$$

The distance from the *Gato Verde* and the vocalizing killer whale was determined by localizing the call in Ishmael 1.0 (David Mellinger). Received level of noise was considered representative of noise levels experienced by killer whales vocalizing in the area because spacing of vessels with respect to killer whales and the *Gato Verde* were variable and dynamic.

Frequency

Background vessel noise is often broadband while killer whale pulsed calls have a clear fundamental frequency making it necessary to define two measures of frequency to make a meaningful comparison. For call files, frequency measure was the minimum frequency of the fundamental of the call. The frequency measure of noise files was the predominant noise frequency. A script in MatLab was written to determine the mean frequency of the noise over the frequency range containing the majority of the power of the signal. The percentage of noise amplitude appropriate for defining the predominant noise frequency was determined from power density spectra. Power density spectra compare the power per unit frequency (dB re 1 $\mu Pa^2/Hz$) to frequency of continuous noise. From the power density spectrum, the range of frequency that accounts for a majority of the power was centered to the peak associated with vessel background noise. The predominant noise frequency was thereby defined to be the midpoint frequency across the majority of the noise pressure (Fig. 2).

Statistical Analysis

Both duration and amplitude parameters of killer whale calls were compared across amplitude of noise with regression analyses. In order to determine if there was a shift in the frequency of killer whale calls, the minimum frequency was compared across predominant noise frequency with a regression analysis. Because the call parameters of interest in this study vary between call types, only the most common call type for SRKW, the S1 call was used (Ford 1987). Behavior may also influence call parameters, so behavior state was noted and only recordings taken during periods of milling were used for analysis.

Results

A total of 80 S1 calls from the SRKW were separated and analyzed for duration, minimum frequency of the fundamental, and RMS amplitude. A sample S1 call spectrogram is illustrated in Figure 3. Background sound files for all 80 calls were analyzed for predominant frequency and RMS amplitude.

The amplitude of southern resident discrete calls was found to increase as the amplitude of vessel noise increased ($p<0.001$, $F_{79,1}=58.62$, Fig. 4). The amplitude of both killer whale vocalizations and vessel noise was greater than expected. Call amplitude ranged from 143 to 183 dB re 1 μPascal at 1 m with the mean call amplitude being 163 dB re 1 μPascal at 1 m. Vessel noise amplitude ranged from 111 to 133 dB re 1 μPascal.

No significant relationship was found between vessel noise amplitude and the duration of killer whale calls ($p=0.591$, Fig. 5). The mean duration of S1 calls during this study was 1.15 s.

In order to determine the relationship between killer whale vocalization frequency and vessel noise frequency the predominant noise frequency was determined. For calculations of predominant noise frequency, 60 percent of the total power of the noise was determined by viewing the power density spectrum of a number of noise samples, as this percentage corresponded with a 20 dB drop from the peak amplitude (Fig. 2). The mean minimum frequency of S1 calls for this study was 1265.94 Hz and did not show a relationship with predominant vessel noise frequency ($p=0.364$, Fig. 6). Mean predominant noise frequency for this study was 4423.877 Hz.

Discussion

Masking avoidance can occur in three ways. The amplitude or duration of the communication can be increased, or the frequency can be shifted to fall outside the frequency of the masking noise. If vessel traffic in the Haro Strait somehow impedes killer whale communication it would be expected that there would be evidence of the use of one or more of these strategies to overcome the effects of masking. This study investigated the possibility of each masking avoidance scenario.

The alteration of vocalization by increasing amplitude to overcome background noise is known as the Lombard response and has been shown in many taxa from primates to cetaceans (Scheifele et al. 2005). Belugas of the St. Lawrence River were directly tested and showed that noise levels common in their habitat cause a notable Lombard response (Scheifele et al. 2005). In the Haro Strait the varied levels of vessel noise caused by shifting numbers and presence of whale watching vessels enabled comparison of orca call amplitude at various levels of background noise. It was determined that vessel noise levels commonly experienced by SRKWs elicits a Lombard response. This relationship has been investigated before with similar results, however in this current study the effect of vessel noise amplitude was found to have on call amplitude was greater (Holt et al. 2007). In the past limitations of equipment have resulted in a lack of studies that compare calibrated amplitude measures of noise with calibrated source levels of vocalization amplitude making this study a notable contribution to the understanding of the southern resident's acoustic environment.

When comparing vessel noise with the duration of southern resident calls there was not a significant relationship. This was surprising since it would seem a less energy intensive manner in which to avoid masking of calls by vessel noise. Foote (1995) found an increase in the duration of killer whale vocalizations when comparing a period of time with fewer vessels present on the water to a period with increased vessel traffic. It is important to consider that number of vessels is not necessarily indicative of the underwater sound environment. Many quiet vessels present would result in lower vessel noise amplitude than a few very loud vessels making a direct assessment of calibrated vessel noise amplitude important for a comparison of length of calls. Duration may not serve to increase orca signal detection because of the nature of the background noise. Vessel noise is broadband and because the vessels are following the pod it is constant rather than cyclical or random. Increased signal detection through increased duration of communication seeks to transmit information during gaps in background noise (Heil and Neubauer 2003, Johnson 1967). Should these gaps not occur, increasing duration is not likely to cause an increase in detection of the signal.

To investigate the third possible manner of masking avoidance frequency shift of calls was measured and compared to a parameter defined to enumerate predominant noise frequency. Although there was no significant relationship between the minimum frequency of the fundamental of calls and predominant noise frequency it is still possible that an overlap of frequency causes masking of vocalizations. The loudest vessel noise, or the predominant noise frequency, would be the frequency where masking was most likely to occur if it overlapped with a killer whale call making it an appropriate measure of vessel noise frequency. Predominant noise frequency was notably higher than the minimum of the call fundamental but clearly overlapped the upper harmonics. Since most of the amplitude of vessel noise is quite high in frequency it is likely that any potential up-shift in the vocalization frequency would not be useful in masking avoidance, as it would not succeed in clearing the call of the vessel noise frequency.

The background vessel noise in the Haro Strait has now been shown to elicit a Lombard response in the SRKW suggesting that masking if their communication is occurring. An increase in vocalization amplitude seems to be the only manner by which killer whales attempt to counter the effects of masking. It is likely that there is an energetic cost to increasing the volume necessary for the southern residents to successfully communicate while in the presence of vessels. Other behavioral alterations attributed to vessels have been estimated to cause an increase energetic cost as well as a loss of feeding opportunity (Williams et al. 2006). These issues may also combine when considering the vocal behavior of killer whales. A modest increase in energy cost of vocalizing to communicate with other pod members may be compounded by less efficient foraging if the communication is unsuccessful or the echolocation clicks are also influenced by vessel noise. Such considerations could result in higher estimates of the energetic cost of whale watching vessels to the southern residents.

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Figures

Figure 1. Map of San Juan Islands, Washington, USA. The study area consisted of the waters around San Juan Island. Recordings were most commonly made in the waters of the Haro Strait.

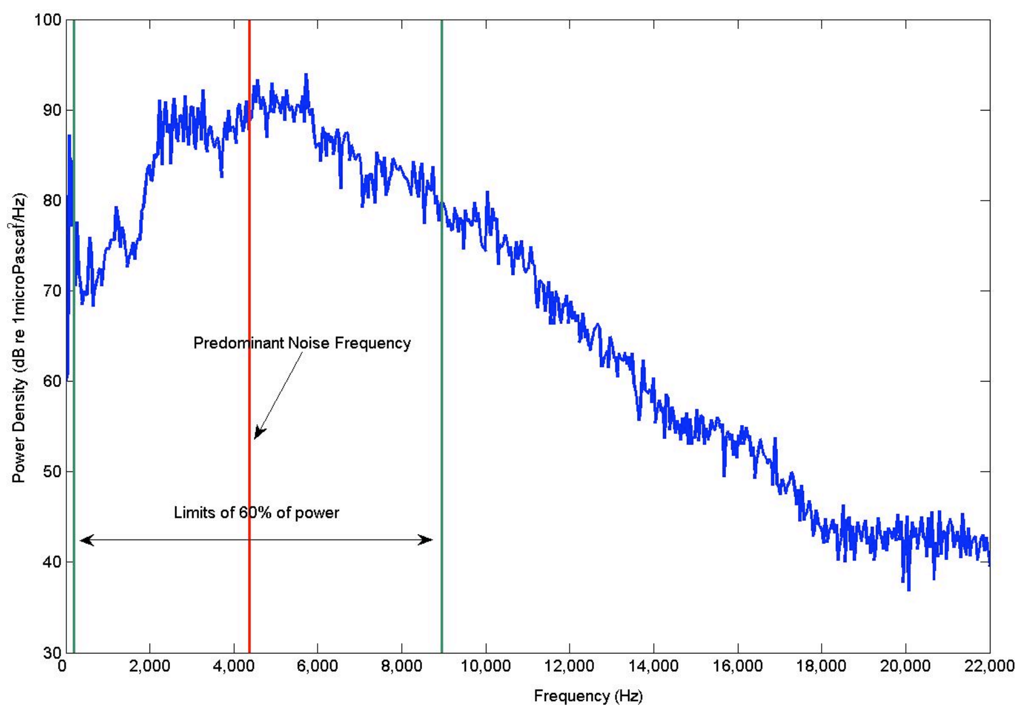

Figure 2. Sample power density spectrum of vessel noise. The area defined to be the majority of the power or a 20dB drop from peak was found to include 60% of the power of the noise and is bracketed by dark green lines. The predominant noise frequency, defined as median frequency over range of frequency included in 60% of power is noted as the red line.

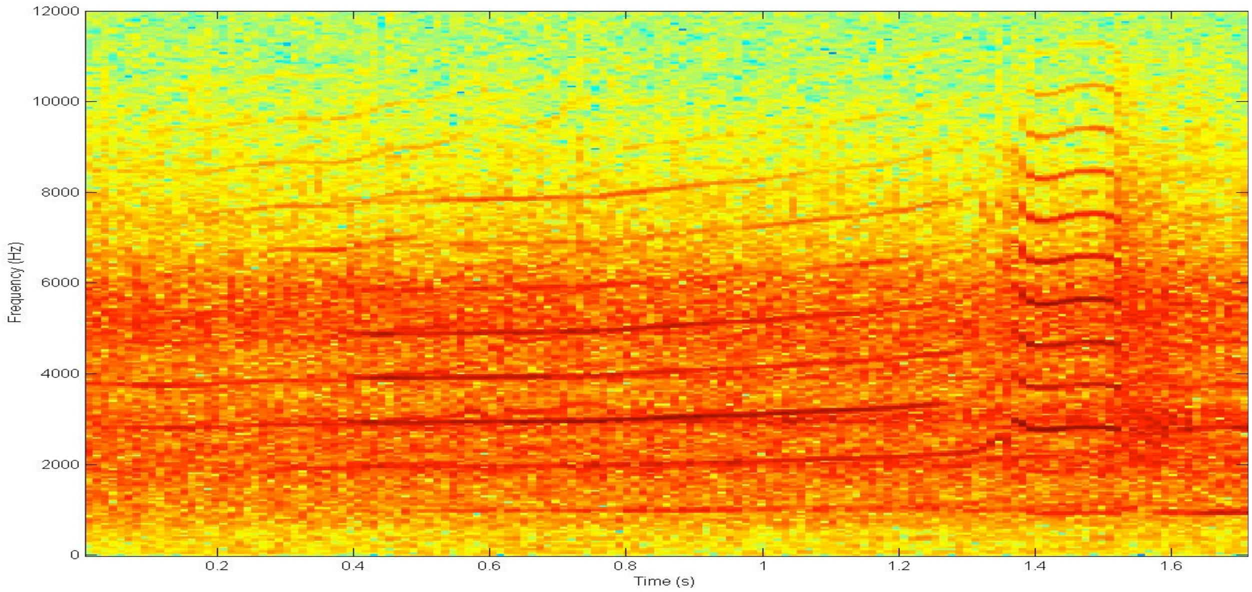

Figure 3. Sample spectrum of S1 call viewed in MatLab with a sampling rate of 44100 and a Fast Fourier Transform (fft) of 1024.

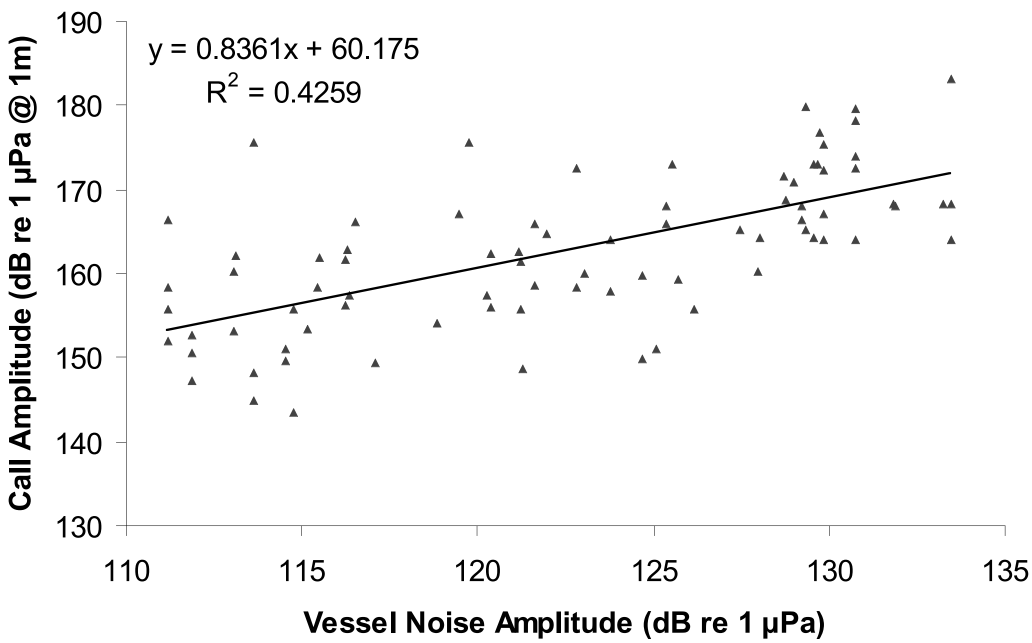

Figure 4. Regression of source level killer whale call amplitude across vessel noise amplitude. $F = 58.61792$; $p < 0.001$; $DF = 79$

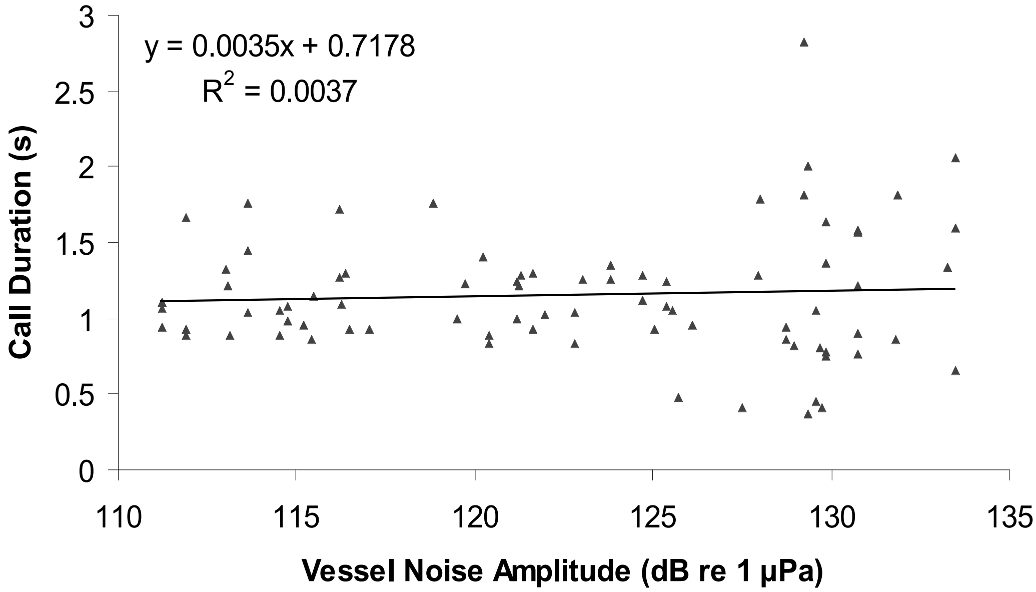

Figure 5. Regression of orca call duration across vessel noise amplitude.

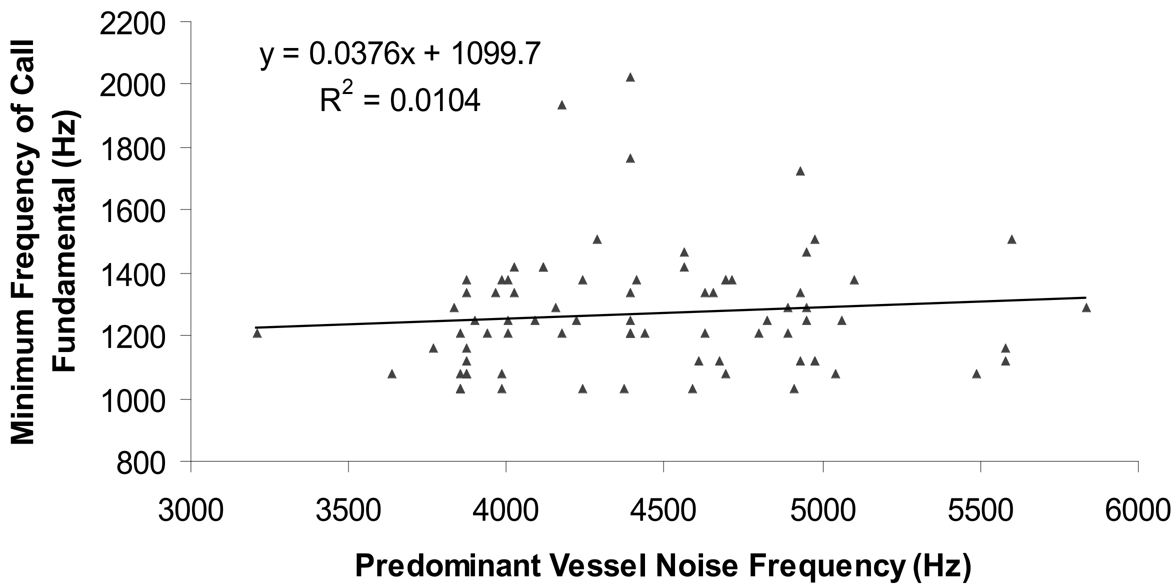

Figure 6. Regression of call fundamental frequency minimum to predominant vessel noise frequency.