CHARACTERIZATION OF SPERM WHALE VOCALIZATION ENERGY BASED ON ECHOLOCATION SIGNALS

Hannan Lohrasbipeydeh⋆, *Tom Dakin*†, *T. Aaron Gulliver*⋆, *and Adam Zielinski*⋆

⋆Department of Electrical and Computer Engineering, University of Victoria
†Ocean Networks Canada, University of Victoria
PO Box 1700, STN CSC, Victoria, BC Canada V8W 2Y2
lohrasbi@uvic.ca,tdakin@uvic.ca,agullive@ece.uvic.ca,adam@uvic.ca

ABSTRACT

Sperm whales (Physeter macrocephalus) emit a train of impulsive echolocation signals called "clicks" when diving in search of food. These acoustic signals can be divided into "usual clicks" and "creaks". The frequency spectrum of these broadband transient signals is between about 500 Hz and 24 kHz, but most of the energy lies between 2 and 9 kHz. The usual clicks have an inter-click interval (ICI) of 0.5-2 s, whereas the ICI of creaks is less. These click signals consist of multiple pulses which are related to the structure of the sperm whale head. An analysis of these signals is presented based on real data from the Atlantic Undersea Test and Evaluation Center. The motivation is the design of a click energy based sperm whale detector which exploits the characteristics of these signals.

***Index Terms*—** Sperm whale, Impulsive broadband signals, Click, Creak, Energy detection

1. INTRODUCTION

Increased human activity on the sea surface such as acoustic navigation, air gun operation, sonar and shipping has resulted in tremendous acoustic interference in the ocean [1]. The effect of this interference on the natural behaviour of sperm whales (Physeter macrocephalus), is a serious concern since they are an endangered species. Tracking sperm whales and identifying flukes are two techniques scientists can employ to monitor whale behaviour. Thus, passive classification, detection and localization of sperm whales has been of increased research interest in the last decade. While their diving behaviour has been studied, little is known about the corresponding click characteristics, which can be used in classifying behavior.

Sperm whales can dive to depths of 2000 m or more in search of food [2]. They generate echolocation signals called "clicks" when diving which can be detected at long distances [3]. These impulsive acoustic signals have non-stationary broadband characteristics due to the time-varying click rate [3, 4]. These clicks are utilized for both communication and echolocation [5]. When foraging, sperm whales produce two different click patterns called "usual clicks" and "creaks". Usual clicks are used for echolocation when searching for fish and squid [6]. Creaks are generated by increasing the click repetition rate and are employed when prey are nearby. Thus, the time interval between clicks can be used to classify sperm whales behaviour.

The click signal received depends on the orientation of the whale with respect to the hydrophones. On-axis clicks are in the direction of the hydrophone, while off-axis clicks are a distorted representation of the on-axis clicks depending on the orientation [7]. In this paper the hydrophones employed are omnidirectional. The click duration depends on the size of the mammal and its orientation, and is typically from 10 to 20 ms [8].

Each sperm whale click is composed of multiple pulses which can be characterized by the physical structure of the sperm whale head [9]. The time interval between pulses is a function of the length of the spermaceti organ as this is the distance between the air sacs at either end of the head. The signal level is sufficiently high with respect to the underwater ambient noise so that it can be used for whale detection. This paper considers the characteristics of these acoustic signals in terms of energy and frequency. The motivation is the design of an accurate energy detector for sperm whale detection and localization.

The remainder of this paper is organized as follows. Section 2 presents the acoustic signals generated by the sperm whale. In Section 3, the acoustic characteristics of usual clicks and creaks are examined. The multiple pulse structure of the clicks are described in Section 4. The click energy is investigated in Section 5 using real sperm whale data from the Atlantic Undersea Test and Evaluation Center. Finally, conclusions are given at Section 6.

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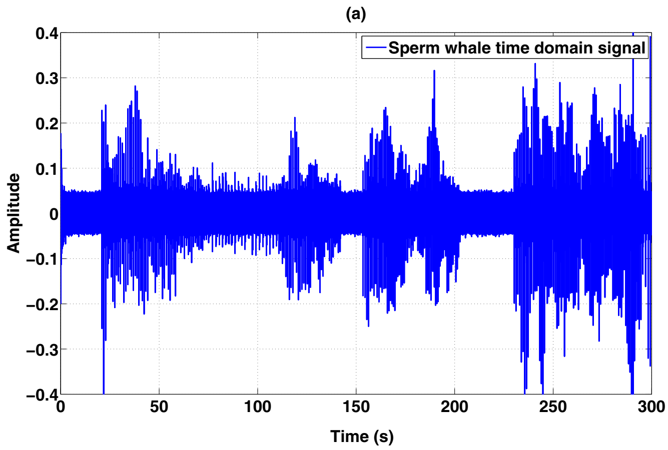

Fig. 1. A typical sperm whale signal in the time domain.

2. SPERM WHALE HEAD STRUCTURE

The head of a sperm whale consists of two main components called the the spermaceti organ and junk. The spermaceti organ spans the longitudinal axis and is filled with spermaceti oil. It is surrounded by a membrane called the case. The junk consists of compartments of spermaceti oil separated by tissue. Sperm whale respiration is via two nasal passages running through the head. The left passage goes from the skull to the blow hole along the left side of the spermaceti organ. The right nasal passage runs between two air cavities called the distal sac and frontal sac and passes underneath the spermaceti organ. The distal sac is connected to the blowhole and the end of the left passage. It contains phonic lips called the museau de singe or monkey's muzzle.

The museau de singe forces air through the right nasal passage which generates an impulsive series of clicks. These clicks have a pulse structure due to reflections through the spermaceti organ. The frontal sac lies near the cranium and acts like a reflector sending signals back thorough the spermaceti organ. These reflections occur over a period of a few milliseconds resulting in a multi-pulse click structure. The delay between the pulses in each click depends on two parameters, the speed of sound in the oil-filled spermaceti organ, and the length of this organ. Since this length is a function of the size of the whale, the pulse structure of a whale can be used for identification.

The sperm whale is the largest animal that uses clicks for communication and echolocation. Although sperm whale acoustic signals are similar to those of smaller whales and dolphins, there are significant differences due to their physiology [13]. Thus the clicks are unique to the species and can be used for species classification.

3. SPERM WHALE ACOUSTIC SIGNALS

In this section, the sperm whale acoustic signal is examined. Sperm whales are prodigious divers that can dive vertically to depths of 2 km or more in search of food such as squid and fish. They remain on the sea surface for approximately 10 min for breathing and then dive from 30 to 90 min before returning to the sea surface [3], [10]. Sperm whales generate signals called "clicks" that are used primarily as echolocation signals. The duration of these broadband impulsive signals depends on the sperm whale size and varies from 10 to 20 ms. The peak power level of each click is approximately 171.2 dB re: 1 μPa [11].

For the usual clicks, a series of clicks is transmitted every 0.5 to 2 s with a slow progressive variation in the repetition rate. The time interval between clicks is called the Inter Click Interval (ICI) [12]. If prey is present, creak clicks are utilized in which the click rate increases to approximately 10 clicks per second [10], [13]. The clicks are a series of spaced pulses with decaying amplitudes that are generated by the air sac located in the sperm whale head. Figure 1 shows a sperm whale signal in the time domain. This signal consists of several clicks including both usual clicks and creaks. A single click in the time and frequency domain is shown in Fig. 2. This indicates that the majority of the signal energy lies between 2 and 9 kHz.

Figure 3 shows the reflections of a single click from the sea surface and sea bottom. These reflection can be used for localization based on the time difference of arrival of the direct path and reflected path signals from the sea surface and sea bottom [14]. The sea surface echo typically arrives soon after the direct path signal, and can have significant energy. Thus it should be accounted for in the design of a whale detector based on signal energy.

4. THE MULTIPLE PULSE CLICK STRUCTURE

Each click consists of several pulses with short time intervals between them. Figure 4 shows a typical on-axis click signal in which three distinct pulses can be identified. The initial pulse, P_0, is produced by the sperm whale museau de singe while P_1 and P_2 are generated by reflections from the frontal and distal sacs. P_0 has the least energy, with the majority contained in P_1. Zimmer et al. [3] have shown that there is a short pulse between P_0 and P_1 called $P_{1/2}$ which is a reflection from the frontal sac, but it is often merged with P_0 or P_1.

The P_2 pulse is produced by click energy reflected through the spermaceti organ. Gordon [8] has shown that the spacing between the pulses in a click, called the Inter Pulse Interval (IPI), can be used to estimate the size of the sperm whale. Note that the IPI differs from the ICI defined earlier. In addition, an off-axis click pattern will differ from an on-axis pattern due to the orientation of the whale.

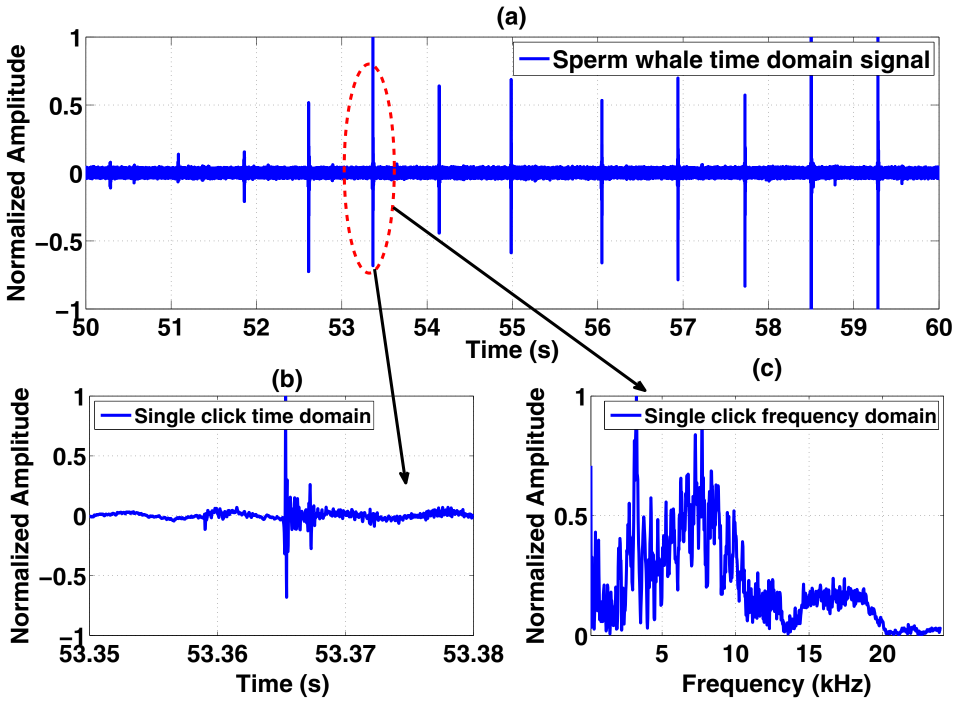

Fig. 2. Sperm whale signals: (a) time domain (b) single click in the time domain, and (c) single click in the frequency domain.

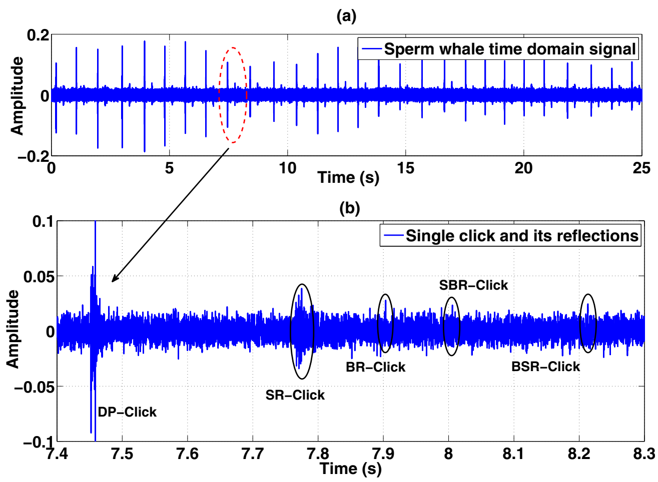

Fig. 3. Sperm whale click reflections: (a) a typical train of clicks, (b) a single click and the corresponding reflections, direct path (DP), surface reflection (SR), bottom reflection (BR), surface bottom reflection (SBR), bottom surface reflection (BSR)

5. CLICK ANALYSIS

The sperm whale acoustic data used to analyse the echolocation clicks was obtained from the Atlantic Undersea Test and Evaluation Center (AUTEC) which is located on the east coast of Andros Island, Bahamas. The data set considered contains both usual clicks and creaks and was recorded by 5 hydrophones over a 25 min period with just one sperm whale present. The data was sampled at 48 kHz at a depth of 2000 m. Further information regarding this data set can be found in [12].

On-axis sperm whale clicks usually have the majority of the energy contained in the P_1 pulse. Figure 5(b) shows the energy of a single click signal obtained using an energy detector. The noise level is assumed to be 10% of the peak amplitude (given by P_1). This figure indicates that the P_1 energy Φ_1 is 62.6% of the total click energy, while 4.9% and 11.6% of the energy is contained in P_0 and P_2, respectively. The remaining energy (20.9%), is considered to be noise. Thus an energy detector which determines the start of the P_1 pulse would be most suitable for sperm whale detection, as this pulse has the majority of the signal energy.

The power spectrum of the sperm whale click, which provides the distribution of the signal energy with respect to frequency, is given in Fig. 6. This shows that most of the click energy (91%) is contained between 2 and 9 kHz.

The decaying characteristic of sperm whale clicks results in both low and high frequency components. Low and high

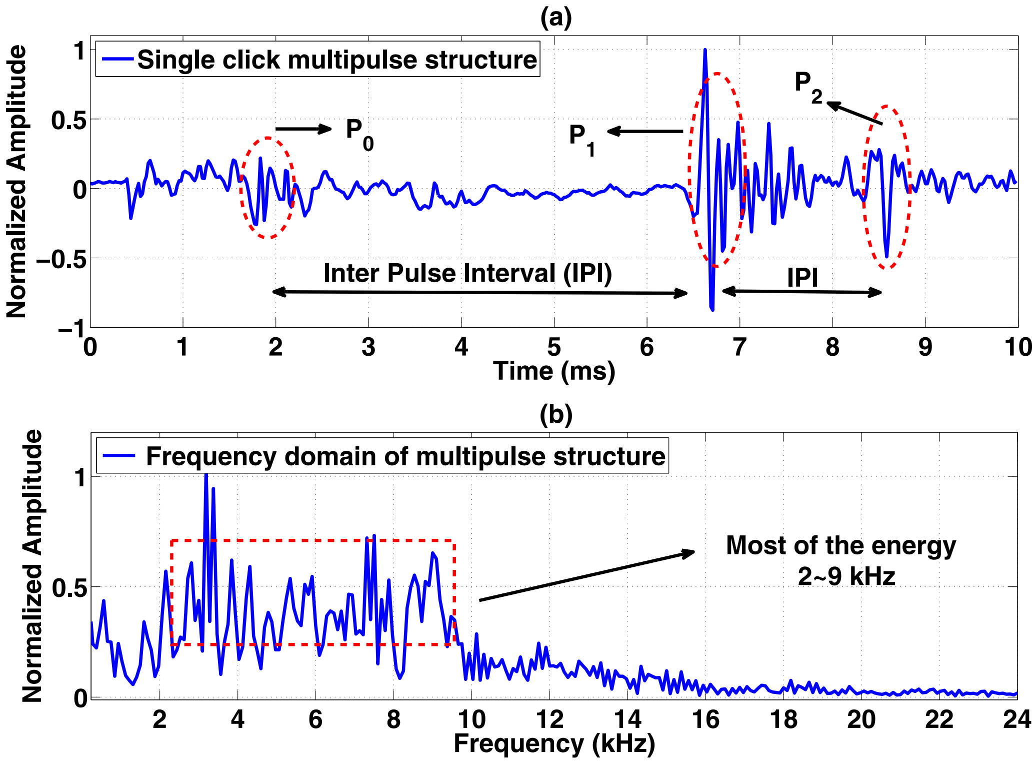

Fig. 4. Sperm whale multiple pulse click signal structure: (a) time domain, and (b) frequency domain.

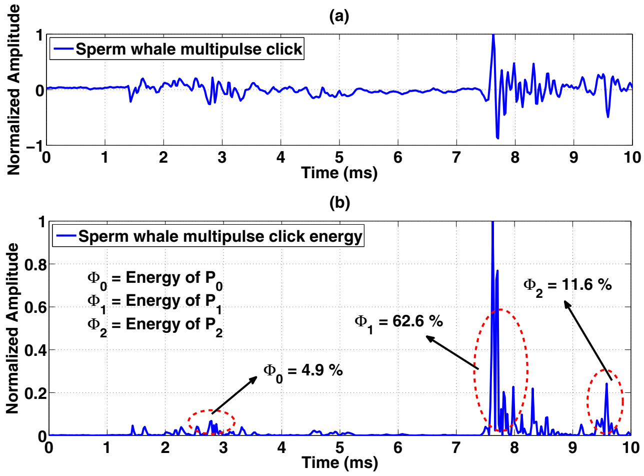

Fig. 5. Sperm whale multiple pulse click signal: (a) time domain signal (b) signal energy.

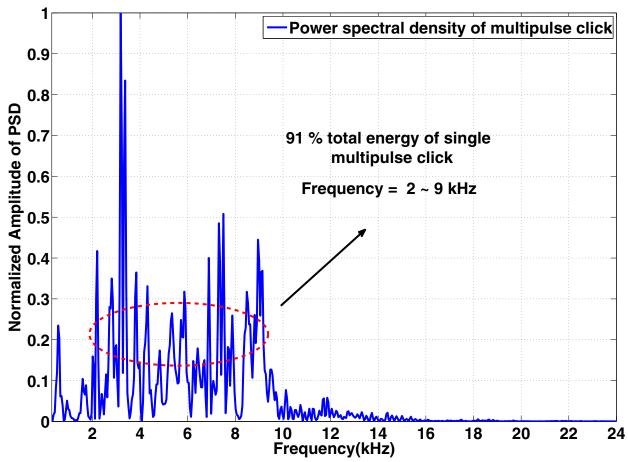

Fig. 6. Power spectral density of a sperm whale click signal.

pass filters were employed to classify the energy in the click pulses, and the results are shown in Table I. Hamming windows were used with a cutoff frequency of 12 kHz. Each row shows the percentage of the click energy contained in Φ_0, Φ_1 and Φ_2. This shows that a high pass filter (HPF) can be used to increase the percentage of the energy in P_0, which will be useful in detecting the start of a click.

6. CONCLUSION

In this paper, the characteristics of sperm whale click signals have been examined. The physical anatomy of the sperm whale head was discussed to show how the clicks are generated. The click signals consist of multiple pulses, and the structure of these signals was analysed in terms of the energy and frequency spectrum. It was shown that most of the energy is contained in the P_1 pulse. Results were presented using real data from the Atlantic Undersea Test and Evaluation Center.

Table 1. Sperm Whale Click Pulse Energy in the Frequency Domain

	$P_0(\%)$	$P_1(\%)$	$P_2(\%)$
Click	4.9	62.6	11.6
LPF	4.4	62.1	11.8
HPF	16.0	70.5	0.9

7. ACKNOWLEDGEMENT

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