Wavelet De-noising with Independent Component Analysis for Segmentation of Dolphin Whistles in a Noisy Underwater Environment

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Abstract **– Bottlenose dolphins (*Tursiops truncatus*) are the most widely studied species of dolphin and are known to produce a complex mixture of different types of sounds. They are believed to communicate through frequency-modulated pure tones (whistles), and produce broadband clicks or click trains for echolocation while investigating their environment. They also produce a large range of other types of sounds variously described as barks, grunts, groans, etc. To further our aim of 2-way acoustically mediated communication with dolphins to study dolphin cognition, we need to separate Bottlenose dolphin whistles from noisy underwater recordings, which not only consist of whistles, but also broadband echolocation clicks, water splashes and other sources of ambient noise. Independent Component Analysis (ICA) has been successfully used for the separation of independent sound sources in many applications. In this paper we will discuss the use of ICA to separate dolphin whistles from other underwater sound sources.**

1 Introduction

Dolphins are believed to one of the most intelligent mammals. Scientific research with the goal of understanding how dolphins communicate has been ongoing since the early 1970's. Recent research has mainly focused on classifying and understanding the meaning of natural dolphin vocalizations, and also on how humans can communicate with these intelligent animals. Dolphins are known to communicate primarily through the use of frequency modulated pure tones, with whistles being the main area of interest. However, trying to extract these signals effectively and efficiently from underwater recordings has always been difficult because recordings of many marine mammal vocalizations include a combination of signals from echolocation clicks, vocalisations that seem to have an emotional content and other fairly nondescript sounds, snapping shrimp in warm shallow coastal waters (impulsive noise), general background noise and other specific sources of noise such as boats, water pumps, etc. We explore the use of ICA to separate whistles from the other components of noise. In order to pursue our goal of 2-way acoustically mediated communication with dolphins, we need to extract dolphin whistles from other animal generated sounds and environmental noise. The characteristics of the different noise sources will be discussed in the following section.

2 Various Sources of Acoustic Signals

Snapping Shrimp:
In warm shallow waters, the marine crustacean Stomatopoda, commonly called snapping shrimp (family *Alpheus* and *Synalpheus*) produces sounds that dominate the ambient noise above 2 kHz. These sounds are produced by an extremely rapid closure of the shrimp's snapper claw. This closure produces a high velocity water jet leading to the formation of a cavitation bubble, which collapses rapidly, causing a loud broadband snapping sound. Snapping shrimp are often found in such large numbers that there is a permanent crackling background noise in warm shallow waters throughout the world. These snapping sounds can be as loud as 190 dB re 1 μPa at 1 m. As ambient noise from snapping shrimp is composed of impulsive noise sources, the resulting probability distribution function fits a symmetric alpha stable distribution [1]. Figure 1.(b) shows the spectrogram of the snapping shrimp noise recorded in Singapore waters.

Whistles:
Dolphins are believed to whistle using frequency modulated pure tones in order to communicate with con-specifics (dolphins of the same species). Dolphins produce many

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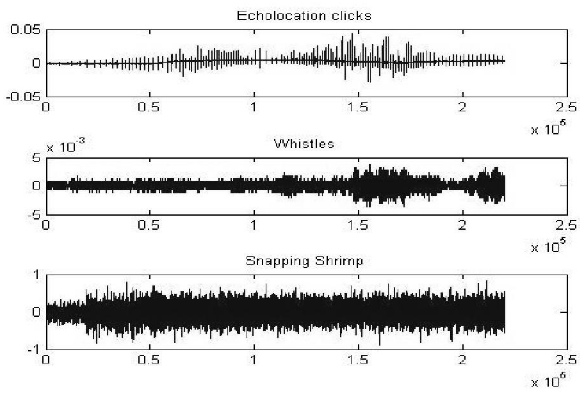
different types of whistles. One whistle which dolphins use frequently and which seems to be specific to an individual is called a 'signature' whistle. This appears to serve to identify an individual dolphin to its group members since each dolphin develops a signature whistle that is uniquely its own. Dolphins do not appear to be born with a signature whistle. Calves develop their signature whistles over the four to six month period after birth. Each dolphin's signature whistle pattern is distinctive, yet certain parts of the whistle stay constant while other parts of the whistle change with changing circumstances. This suggests that whistles might communicate other information or serve other purposes than simply to indicate an individual's presence. Dolphins have an exceptional ability to mimic diverse sounds and have been recorded making the signature whistles of other dolphins. Bottlenose dolphin whistles commonly fall within the bandwidth 5 to 15 kHz but can peak at over 20 kHz with 35 kHz being the generally recognized maximum frequency [2; and our own observations]. Figure 1. (c) shows the spectrogram of a dolphin whistle in the absence of background noise.

Echolocation Clicks:
Dolphins produce broadband clicks sometimes in click trains, during echolocation (biosonar activity). These clicks are used mainly for navigation and to detect and identify objects in the dolphin's environment, including fish and other prey. Via this complex system of echolocation, dolphins can determine the size, shape, speed, distance, direction of movement, and even some of the internal structure of objects in water. A spectrogram of echolocation clicks is shown in Figure 1. (d). The frequency range for echolocation clicks is 0.25 to 220 kHz [2]. Also, dolphins' echolocation clicks have amplitudes that range from 150 to 230 μPa (peak to peak) [3].



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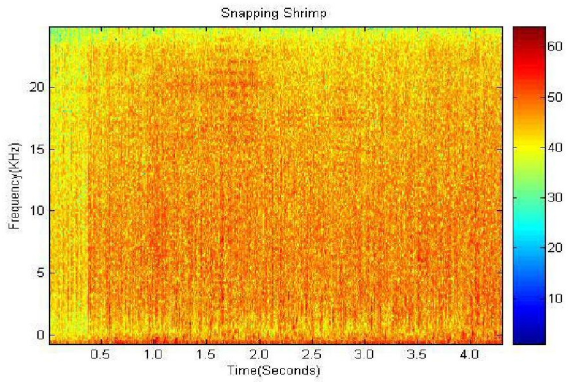

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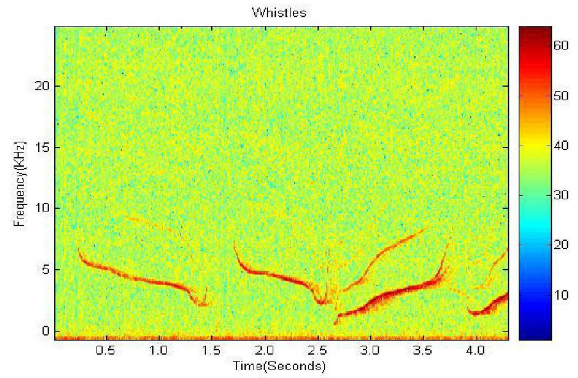

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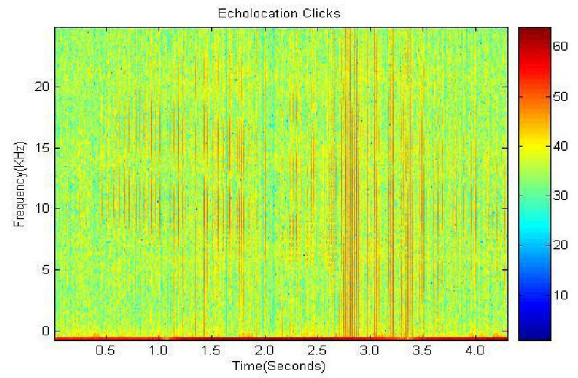


(d)

Figure(1) (a) Time series of various source signals. Spectrograms of: (b) Snapping shrimp noise, (c) Whistles, and (d) Echolocation clicks.

3 Problem Formulation

Dolphins are able to produce echolocation clicks and whistles simultaneously. Often, both of these components are present in sound recordings, together with other background noise such as from snapping shrimp which complicates the analysis of recording made during studies of dolphin communication and cognition. Since whistle patterns play an important role for researchers involved in behavioral studies of dolphins, there is a need to subtract other sound sources from the whistle to produce a clear acoustic signal.
We explore the use of Independent Component Analysis (ICA) for the separation of whistles from the other sources of noise, which are received on multiple hydrophones.

4 Modelling the Mixed Signals at the Receiver

In order to test the ability of ICA to separate the sources we derive the simple model with which to create test data based on the proposed geometry of the proposed field trial. The geometry used for the model and field trial is shown Figure (2).

The received time series on the i^{th} hydrophone can be expressed as

$$h_i(t) = \sum_{j=1}^{3} \left(\frac{1}{d_{i,j}^2} \right) s_j \left(t - \frac{d_{i,j}}{c} \right) \qquad (1)$$

Where $d_{i,j}$ is the distance between the i^{th} hydrophone and j^{th} and c is the speed of sound in ms^{-1}. This model includes the transmission and the delay.

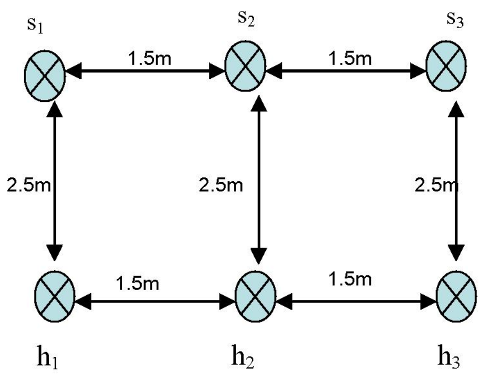


Figure (2) Mixing Model for the experiment

Ignoring the time delays, the mixing matrix can be expressed as

$$H(t) = \left(\frac{1}{d_{ij}^2} \right) S(t) \qquad (2)$$

Since the mixing matrix is known the mixed signals can simply be inverted using the inverse mixing matrix

$$S(t) = \left(\frac{1}{d_{ij}^2} \right)^{-1} H(t) \qquad (3)$$

The spectrograms shown in Figure (4), shows the result of the inversion. Of course in the real situation the mixing matrix is unknown and the ICA algorithm estimates the mixing matrix for use in the conversion and separation of the sources.

5 Experimental Set-up

Two hydrophones were used to emit pre-recorded dolphin whistles and an echolocation click series, respectively. This was carried out at a seawater marina such that the third component of commonly encountered noise, snapping shrimp, was also included due to the naturally occurring population of this animal in the marina. In the model snapping shrimp were localized in space in this real situation that coming from multiple directions
The signals were recorded using three B&K 8103 hydrophones which were spatially separated at 1.5 m apart at a depth of 1m below the surface of the water. The signals were amplified using a B&K NEXUS 2692 hydrophone conditioning amplifier with 4 input channels, and then sampled at 44.1 KHz using a data acquisition device from National Instruments (NI DAQ 6070E). The experimental set-up is shown in Figure (3).

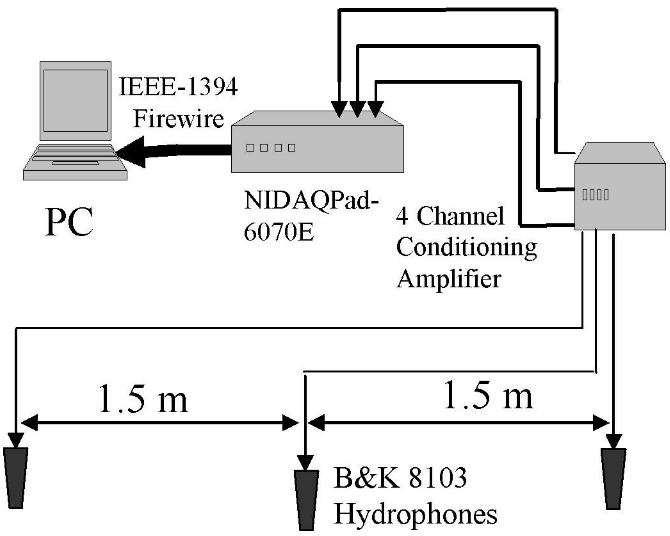
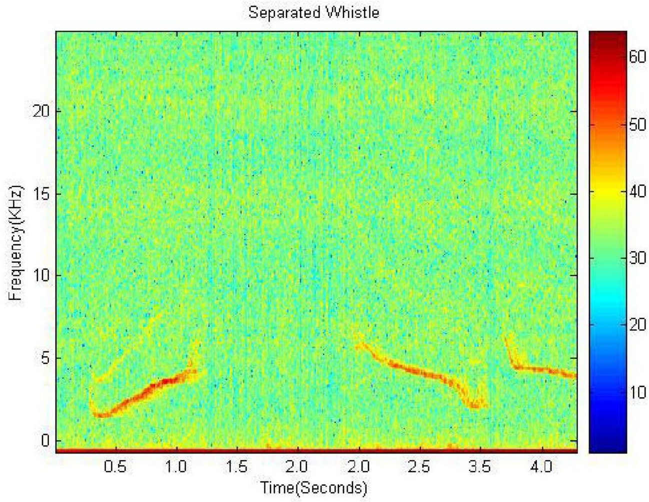


Figure (3) Equipment setup for the experiment



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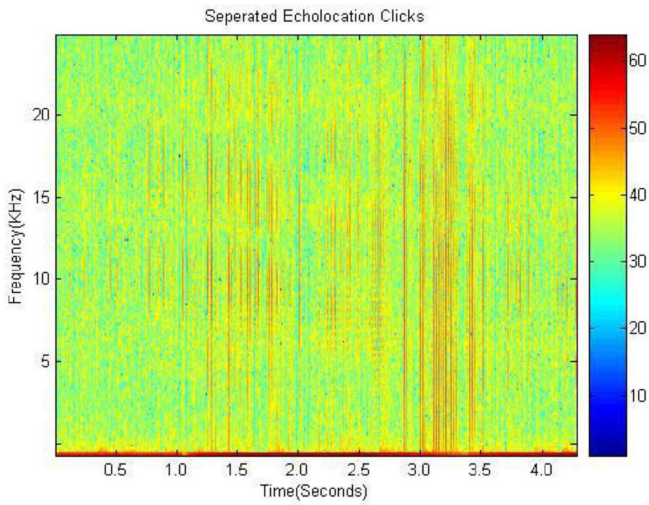

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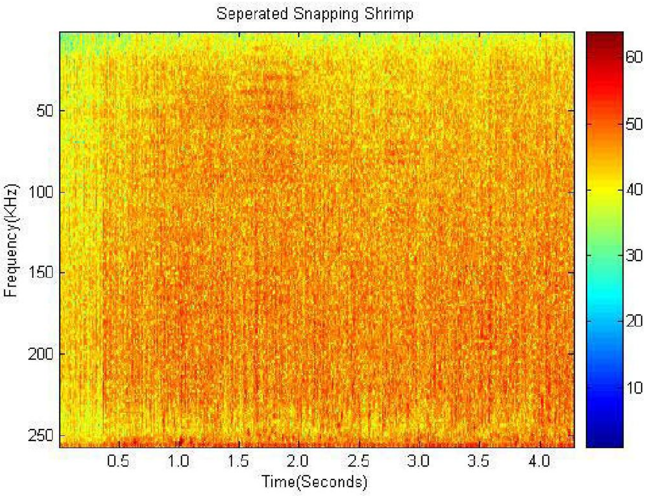
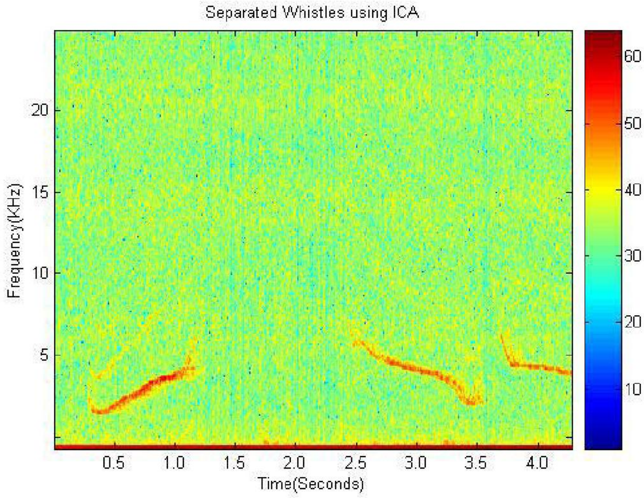


(c)

Figure (4) Seperated Signals by multiplying with the inverse of known mixing matrix (a) Whistle (b)Echolocation Clicks (c)Snapping shrimp



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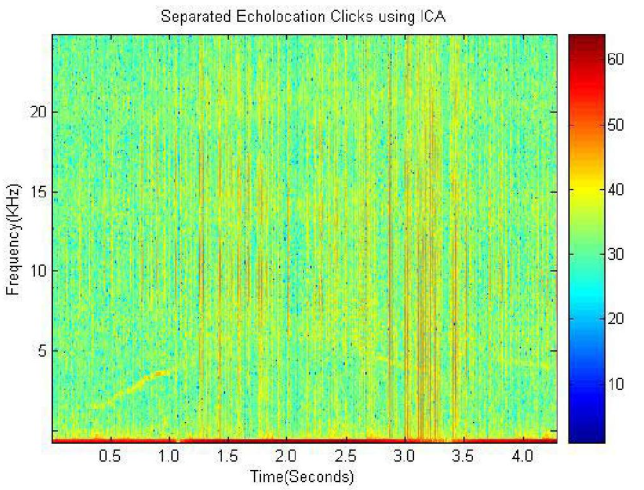

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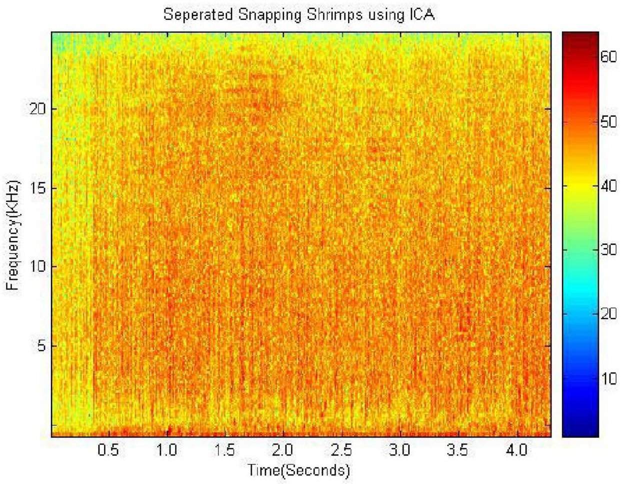


(c)

Figure (5) Seperated signal using ICA(FPICA) by estimating the mixing matrix (a)Whistles(b)Echolocation Clicks(c)Snapping Shrimp

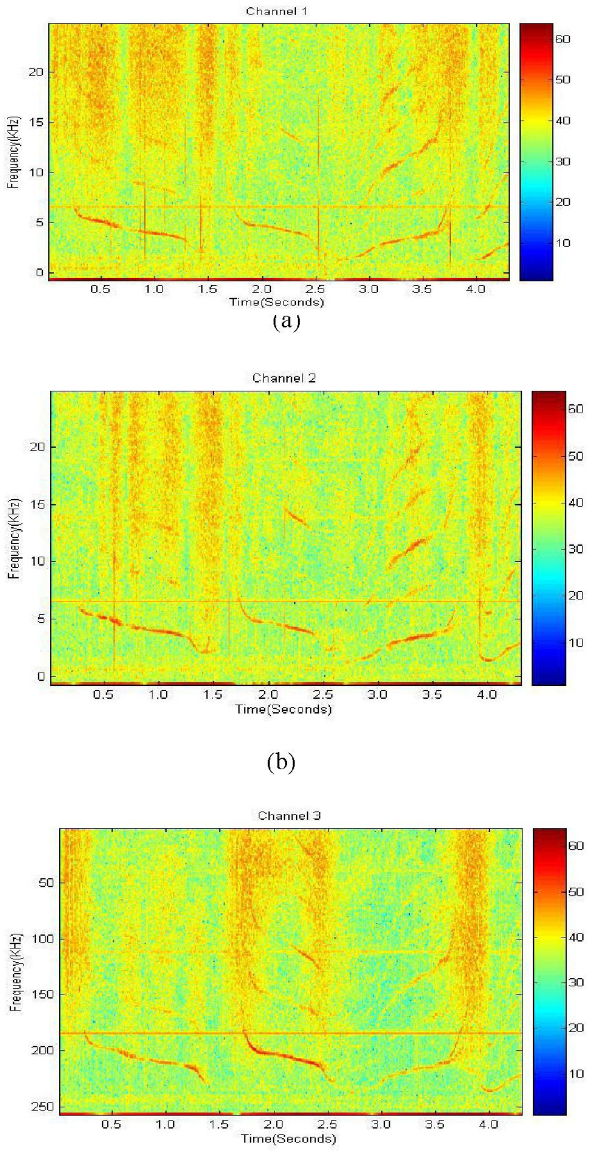


Figure (6) Spectrograms of signals recorded on different channels from the conditioning amplifier (a) Channel 1, (b) Channel 2, and (c)Channel 3

6 Simulation Results

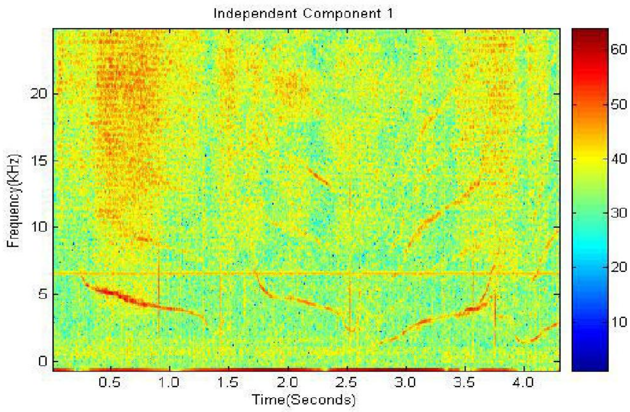
Acquired signals were loaded into ICALAB, a software package based on MATLAB that runs an ICA Algorithm. The spectrograms of the three received signals are shown in Figure(6).Each channel has been whitened prior to the application of the ICA algorithm, in order to make the signal as independent as possible . Four different algorithms were tested, and Table 1 shows the performance of the different algorithms.

Table 1. Performace of various algorithms

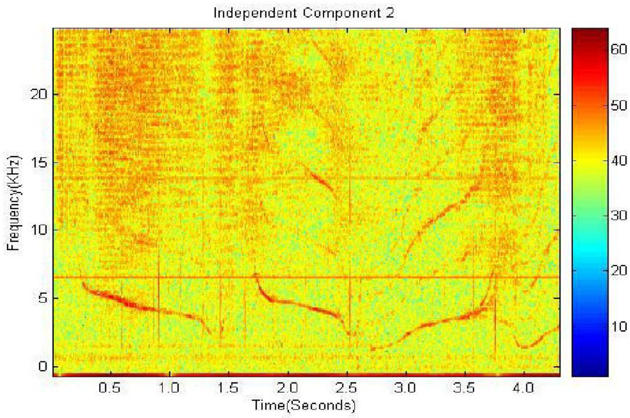
Algorithm	Performance of Separability	Performance of Orthogonality
FPICA	51 %	0.00063
JADE OP	39.9%	0.00058
JADE TD	35.7%	0.00072
ERICA	34.5%	0.28190

FPICA-Fixed Point ICA
JADE OP-Joint Approximate Diagonalisation of Eigen Matrices Optimised
JADE TD-Joint Approximate Diagonalisation of Eigen Matrices with Time Delay
ERICA-Extended Robust ICA

Since component 1, shown in Figure 7(a) contained most energy from the dolphin whistle, it was selected for further de-noising. The wavelet based de-noising algorithm [4] regards the signal as being made up of four components: tonals; transients; time/frequency transients; and spectrally smooth noise. The algorithm performs the automated detection and extraction of these four different types of signals. The results after de-noising are shown in Figure (8).



(a)



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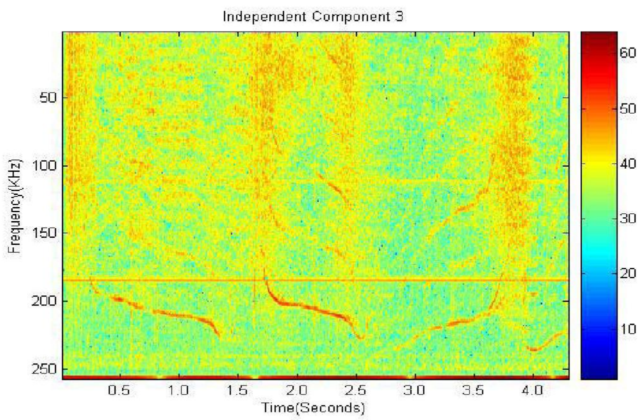

(c)

Figure (7) Spectrograms of signals after ICA Algorithm (FPICA) Components (a) 1, (b) 2 and (c) 3 respectively

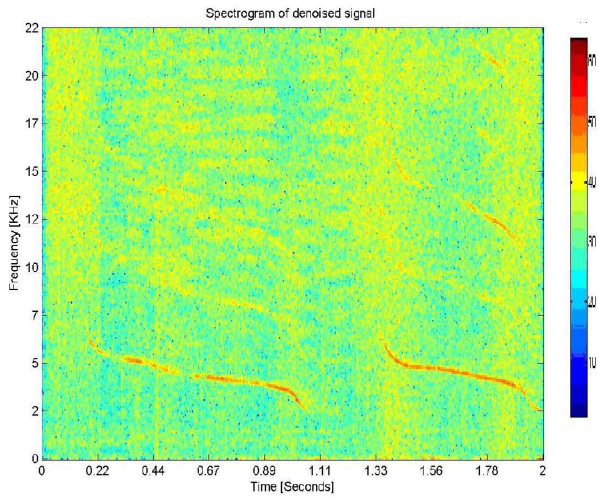

Figure (8) Spectrogram of the signal after de-noising

For comparison, Channel 1 of the received signal was de-noised using the wavelet algorithm without ICA and the spectrogram is show in Figure (9).

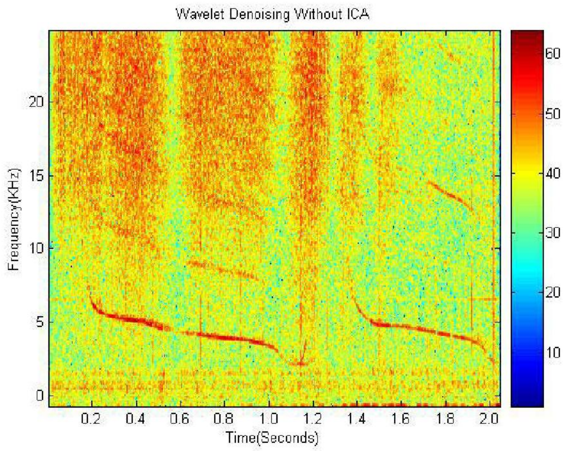

Figure (9) Spectrogram of Channel 1 input after wavelet de-noising without ICA.

7 Discussion & Conclusions

Our aim was to separate dolphin whistle acoustic signals from echolocation clicks and other ambient noise.

In the model based application the ICA separated the source signals very well, however in the real situation it does not perform as well. ICA Algorithms are generally based on a Gaussian noise model however snapping shrimp have a noise distribution which is symmetrically alpha stable (Non-Gaussian) [1]. This noise from snapping shrimp has different characteristics compared with dolphin vocalizations which are frequency modulated tones (whistles) and high frequency transients (echolocation clicks). As such, the ICA Algorithm is unable to successfully separate the different sources with a useful percentage of accuracy (Table 1). The use of the ICA algorithm was partially successful in separating snapping shrimp. The wavelet de-noising method proposed by Seekings and Potter (2003) has been successfully adopted to remove the high frequency transients and the remaining snapping shrimp noise. By using ICA followed by wavelet de-noising, dolphin whistles can be extracted successfully from a noisy underwater environment. The result of wavelet de-noising without performing ICA is seen by comparing Figures 8 & 9. By using ICA followed by wavelet de-noising, dolphin whistles can be extracted successfully from a noisy underwater environment.

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