UNDERWATER TRANSIENT SIGNAL PROCESSING: MARINE MAMMAL IDENTIFICATION, LOCALIZATION, AND SOURCE SIGNAL DECONVOLUTION

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ABSTRACT

Processing marine-mammal signals for species classification and monitoring of endangered marine mammals are problems that have recently attracted attention in the scientific literature. For classification it has been proposed to use methods appropriate for non-stationary signals, such as time-frequency and time-scale analysis. This paper shows that a factor that can significantly affect results from marine-mammal signal processing is the impulse response of the ocean in which the signals propagate. The ocean is a dispersive propagation medium and, therefore, affects the time-frequency characteristics of a propagating acoustic signal. Because of this distortion, feature selection should be performed after the oceanic impulse response has been deconvolved from the recorded signals. The paper also discusses localization of vocalizing marine mammals using matched-field processing and shows how this becomes a part of the deconvolution process.

1. INTRODUCTION

Motivation for processing marine-mammal signals stems from increasing interest in the behavior of endangered marine mammals, reflected in a number of publications in the scientific literature [1, 2, 3, 4, 5, 6, 7] as well as the press [8, 9]. The ultimate goal of the research is to develop tools for the simultaneous localization of mammals and deconvolution of received signals for tracing the originally transmitted time series for species identification.

The potential for marine mammal localization and identification in the ocean by processing mammal-generated sound signals has been demonstrated in [4] and [5, 6] respectively. Weisburn et al. [6] studied the identification of notes produced by bowhead whales. Assuming prior knowledge about the structure of the signals of interest, a matched filter and a hidden markov model were designed for the binary decision problem of presence or absence of the modeled transient signal in a recorded sequence. Learned and Willsky [5] have presented results on biological signal classification based on wavelet packets and neural networks.

2. SIGNAL DISPERSION IN THE OCEAN

The work in [6, 5] is based on time-frequency and time-scale analysis which, in common with other studies in the literature, treats recorded marine mammal signals as "clean" signals—that is, signals that are free from interference or distortion effects imposed by the propagation environment. This is a rough approximation, however. The device used to record the biological signals is located away from the sound-emitting marine mammal, so the recorded signal is the result of the convolution of the transmitted signal and the impulse response of the propagation medium between the source and the receiver. Specifically, if $s(t)$ and $r(t)$ are the transmitted and received signals and $h(t)$ is the impulse response of the underwater propagation medium:

$$r(t) = h(t) * s(t) + n(t), \tag{1}$$

where $n(t)$ is additive noise.

In several communication applications the effect of the channel impulse response is simply attenuation of the propagating signals. The ocean, however, is a highly dispersive medium and tends to affect every frequency of a propagating broadband signal differently. This process distorts the signal properties leading to a waveform with different time-frequency characteristics at the receiver compared to those at the source.

The impulse response $h(t)$ is actually Green's function expressing the way an impulse propagates in the ocean. It is dependent on channel characteristics, such as sound speed profile, geoacoustic properties of the seafloor sediment, bottom depth, and geometry (source and receiver locations).

3. PROPAGATION OF LFM SIGNALS IN A SIMULATED OCEAN

It is known [10] that frequency sweeps are characteristic types of signals for certain groups of marine mammals. The classification of a biological transient as an up- or down-sweep could mean the identification of a particular species. In the present work, using examples of up and down lfm sweeps it is shown that deconvolution of the source signal is necessary before feature selection for species identification.

To illustrate the effect of dispersion on underwater sound, an up-sweep lfm signal with frequency content between 400 and 600 Hz is selected as the source signal. The signal is propagated through a 30 m deep simulated ocean with a sound speed profile described in [11]. Figure 1 shows the dispersion curves (group velocity vs. frequency) for the individual propagating modes. In the 400 to 600 Hz frequency range the modes appear to separate [11]. Mode 2 becomes

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the fastest mode followed by modes 1 and 3. In Fig. 1 we observe intermodal dispersion (the modes separate and travel with different speeds) and intramodal dispersion (different frequencies within the same mode propagate with different velocities). It can be seen that the high frequencies of the second mode travel faster than the lower frequencies. This is not true for the first mode, for which higher group velocities correspond to lower frequencies.

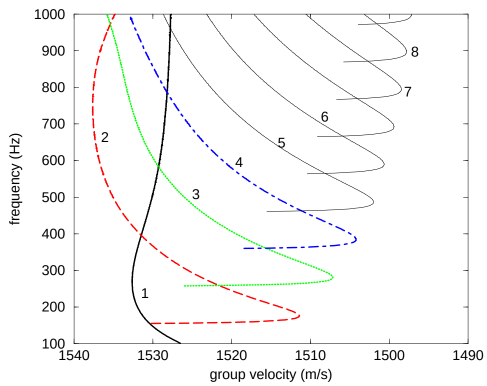

Figure 1. Dispersion curves for the propagation medium.

Figure 2 shows the spectrograms of the source waveform and the received waveform at a depth and range of 15 m and 30 km from the source. The top spectrogram of Fig. 2 shows the up-sweep behavior of the source pulse. The lower frequencies arrive first, followed by the higher ones. The pulse of Fig. 2 (bottom), however, demonstrates a non-linear down-sweep behavior which is in contrast to the original time-frequency picture of the transmitted pulse. The pulse of this second spectrogram is the pulse carried by the second mode of propagation; the other modes, which are separated from mode 2 because of intermodal dispersion (Fig. 1), are attenuated at this distance. Figure 2 also shows that the received pulse (Fig. 2 (bottom)) is of longer duration than the source pulse (Fig. 2 (top)). The extended duration at the receiver is caused by the energy dispersion of mode 2 (intramodal dispersion).

In summary, performing marine mammal classification or identification through time-frequency domain methodologies, one could select the time dependence of the frequency content as a feature. This, however, could lead to poor classification results since a pulse with linearly increasing frequency with time appears as a pulse with completely different time-frequency characteristics when received far from the source. The propagation medium must, therefore, be accounted for prior to attempting feature selection.

4. DECONVOLUTION OF THE CHANNEL IMPULSE RESPONSE

Deconvolution of the channel "contamination" from the recorded marine-mammal signals requires the calculation of the impulse response of the oceanic propagation medium. Estimating the impulse response is an inverse problem that can be approached with matched-field processing methods [12]. Matched-field processing is a term used for those

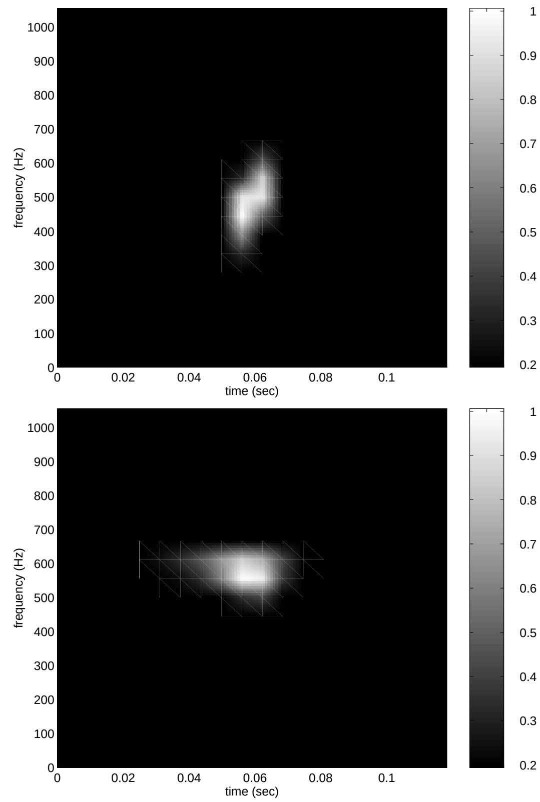

Figure 2. Spectrograms of the transmitted and received pulses.

techniques that estimate environmental or geometry parameters related to underwater communications problems by combining signal processing and the physics of the oceanic waveguide.

It is assumed here that the received signal is measured at an array of vertically separated hydrophones. The array consists of four hydrophones at depths of 20, 40, 60, and 80 m. As mentioned in Section 2, the impulse response for the channel connecting source and receivers depends on the source and receiver location, the sound speed profile, the bottom depth, and the properties of the ocean floor. One can estimate these parameters, and, consequently, the impulse response, by matching the received acoustic signals to replica signals, generated with the help of sound propagation models for candidate values of the parameters. A measure of correlation between real signals and replicas is then calculated; the estimates of the unknown parameters are those values that maximize the correlation.

Conventional matched-field processing is performed in the frequency domain and does not require knowledge of the transmitted waveform. The replica signals are calculated for a source spectrum of unit amplitude and zero phase at every frequency.

Matched-field inversion can be performed in a narrow-band fashion using only a single frequency of the received signal. However, a broadband approach is more appropriate for analyzing whale signals since those signals are broadband waveforms. Moreover, the greater robustness and accuracy of broadband matched-field processing [13] is desirable because of the large number of uncertainties in the whale signal deconvolution problem.

The whale signal considered here as the source waveform is a segment of 0.3 s duration from a whale trumpet call. The spectrogram of the trumpet call, shown in Fig. 3, indicates that the signal carries information between very low frequencies and somewhere below 4 kHz (the sampling rate is 8 kHz). Most information is, however, below 1500 Hz. The selected 0.3 s segment, obtained from the beginning of the trumpet call, is shown in Fig. 4. For this part of the call, most information lies below 1200 Hz.

The signal of Fig. 4 is considered to be the unknown, original source signal that needs to be estimated with deconvolution. For the generation of the received signal at the array of hydrophones, the source was assumed to be located at a depth and range of 30 m and 7 km respectively (the source coordinates will be assumed to be unknown in the estimation procedure that follows). The received signal was then generated using the normal modes approach for sound propagation modeling.

Although information at multiple frequencies improves matched-field performance, the whole bandwidth is not necessary for the inversion. Here, we only use four tones, 250, 500, 750, and 1000 Hz, which, as seen from Fig. 3, appear to be dominant in the first 0.3 s of the call. Frequency-domain replica signals were then obtained (also using normal modes) for the four frequencies and receiver depths of 20, 40, 60, and 80 m.

In order to keep the computations manageable, all environmental parameters are assumed to be known exactly. The only unknowns needed to fully determine the impulse response of the ocean are the source location coordinates, range and depth. Simple linear (Bartlett) processing with incoherent averaging of correlations over the four frequencies is used for the location inversion. With no environmental mismatch present, broadband incoherent Bartlett processing leads to accurate source location estimates even for a low signal to noise ratio.

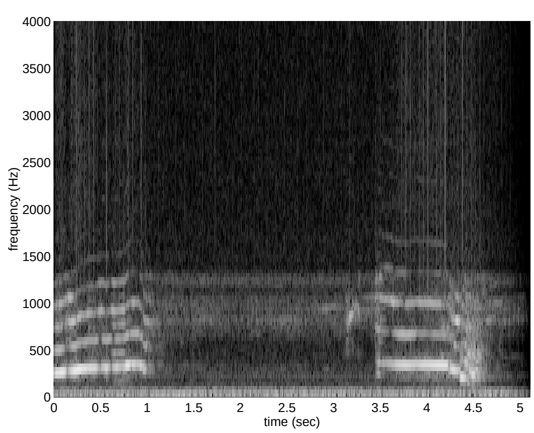

Figure 3. Spectrogram of a trumpet call.

After the successful estimation of the source location and since no other uncertainty is present, the propagation channel between source and receivers is fully determined. The whole bandwidth of the signal (or as much as is computationally reasonable to use) needs to be considered for the calculation of the transfer function of the channel (normal modes operate in the frequency domain). Here the range between 5 and 1200 Hz is used. The lower limit (5 Hz) is imposed by the fact that the 100 m deep waveguide selected here does not support propagation below 5 Hz. The upper limit is chosen to contain most of the signal information. As can be seen in Fig. 3, some information extends beyond 1200 Hz. However, for computational efficiency, the transfer function of the ocean is calculated only up to that bound (normal modes computational requirements increase with frequency).

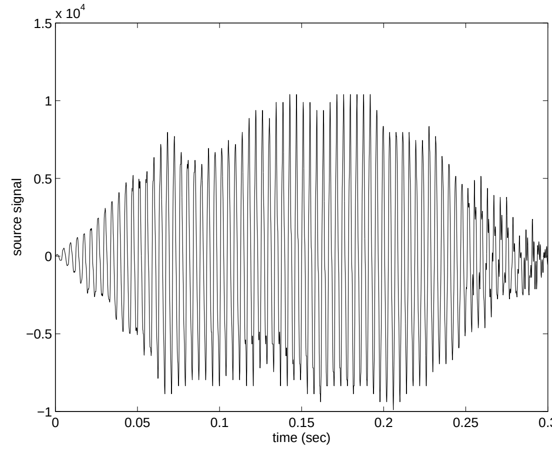

Figure 4. Segment of a whale call.

Deconvolving the channel effects from the received signal is a straightforward task after the transfer function has been computed; the estimated source waveform is found by simply dividing the spectrum of the received signal at a single hydrophone over the ocean transfer function in the 5 to 1200 Hz frequency range and then inverting into the time domain. The result of the deconvolution, the estimated source waveform, is shown in Fig. 5 (top, left). In the same figure (bottom, left), the correlation between the original and estimated waveforms is plotted. The maximum of the cross-correlation is found to be close to 1. A perfect match (correlation of 1) is not possible, even though the ocean environment and geometry were perfectly defined, because of the frequency limitations that have been imposed: the original signal carries information below 5 Hz and above 1200 Hz, which are frequency ranges not accounted for in the deconvolution process.

The procedure described above shows how matched-field processing can be used in order to find the channel impulse response and deconvolve it from a received signal. Successful deconvolution is a result of accurate knowledge of the channel impulse response. If there is an error in the impulse response calculation, it will be reflected in the quality of the deconvolution. The Bartlett processing that was used here to find the source location coordinates assumes that all environmental parameters are accurately known. In realistic applications, however, the environment is not known exactly. The simple Bartlett processor will then result in source location estimates that, more likely than not, differ from the true range and depth of the source. These estimates along with the incorrectly assumed values for the environment will lead to the computation of an inaccurate impulse response.

To show the effect of the mismatch between true and estimated values of the parameters on deconvolution, we assume that the estimates of the source location are 25 m and 7 km for depth and range. The 5 m discrepancy in the source depth estimation is considered to be a relatively small error in source localization (that is, this localization result would have been considered correct, being within 5 m and 0 km in depth and range from the true source location). The new source location values are then used to specify the transfer function or, equivalently, the impulse response of the ocean, which is now incorrect. The result of the deconvolution given the new, "mismatched" transfer function is shown in Fig. 5 (top, right) with the correlation between estimated and true source signals illustrated in the bottom right corner of the same figure. The maximum correlation obtained this time is 0.66, showing the substantial degradation even for a small discrepancy between true and estimated parameters.

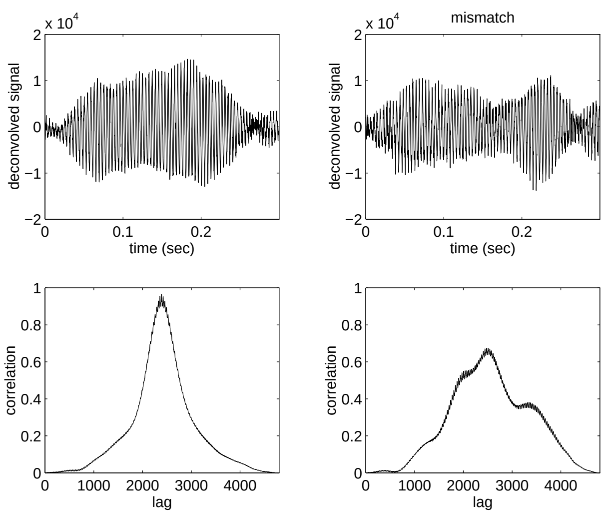

Figure 5. Deconvolved signals and correlations between the deconvolved signals and the originally transmitted whale call.

5. CONCLUSIONS

This paper demonstrated the need for deconvolution of the channel effects from marine-mammal signals, since those effects distort characteristics of the signals useful for classification. A methodology for the task of deconvolution was then proposed. Simulation results showed the importance of accurate estimation of the impulse response prior to deconvolution.

After deconvolution, classification can be performed by choosing appropriate features from the whale signals. Figure 3, showing a time-scale picture of the whale call considered here, indicates that energy distribution with frequency range and number and location of harmonics could be suitable features. Alternatively, classification could be performed using correlation between spectrograms (as the one of Fig. 3), as discussed in [6], with high correlation indicating calls belonging to the same class; or with time-scale analysis methods [5] appropriate for the non-stationary biological signals.

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