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Real-time 3D tracking of whales by echo-robust precise TDOA estimates with a widely-spaced hydrophone array

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Abstract

This paper provides a novel echo-robust and real-time passive underwater acoustic method to track whales using five omni-directional widely-spaced bottom-mounted hydrophones. The interest in online marine mammal monitoring for behavioral studies of endangered species has increased. Practically, these systems are required to be real-time and robust to underwater echoes, which dramatically affect tracking results. To meet these demands, a real-time tracking algorithm was developed with simple but efficient echo cancellation. The processing is all done in the time–domain. After signal decimation, rough time delays of arrival (TDOAs) are calculated, selected and filtered, before precise TDOAs are re-estimated on the original signals. The complete algorithm is tested on real data from the Naval Undersea Warfare Center and the Atlantic Undersea Test & Evaluation Center—Bahamas. The attractive advantage of the method is that it runs two times faster than real-time, but generates similar tracks to other state-of-the-art methods.
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1. Introduction

Processing of marine mammal (MM) signals for passive oceanic acoustic localization is a problem that has recently attracted attention in scientific literature and in some centers like the Atlantic Undersea Test & Evaluation Center—Bahamas (AUTEC), the Naval Undersea Warfare Center of the US Navy (NUWC), or the French Navy research center. Motivation for processing MM signals stems from increasing interest in the behavior of endangered MM [1]. One of the goals of current research in this field is to develop online tools to localize the vocalizing and clicking whale for species monitoring. In this paper we propose a low cost time–domain (TD) tracking algorithm based on passive acoustics. The experiments of this paper consist in tracking an unknown number of whales. Clicks were recorded for 25 min on an open-ocean widely-spaced bottom-mounted hydrophone array. The output of the method is the track(s) of the MM in 3D space and time. The next section briefly reviews studies of source separation methods and the main characteristics of MM signals, then we propose a new TD algorithm for MM transient call localization. Tracking results are given in Section 4, and are then compared and discussed.

2. Problem formulation and background studies

This papers deals with the 3D tracking of whales using a widely-spaced bottom-mounted array in deep water—two main requirements for the localization technique presented here. It focuses on sperm whale clicks; detection and classification are not a concern. The main goal is to build a robust and real-time tracking model, despite ocean noise, multiple echoes, an imprecise sound-speed profile, an unknown number of vocalizing whales, and the non-linear time frequency structure of most MM signals [2]. Background ocean noise results from the addition of several noises: sea state, biological noises, ship noise and molecular turbulence. Propagation characteristics from an acoustic source to an array of hydrophones include multipath effects (and reverberations), which create secondary peaks in the cross-correlation (CC) function that the generalized CC methods cannot eliminate [3]. In previous work (including classification tasks), Fast Fourier Transform (FFT) based techniques have been used [4]. A detection classification and localization model has been developed as part of the US Marine Mammal Monitoring on Navy Ranges (M3R) program [5,6]. In this model, the detection is a two-stage process that uses a binary thresholding on FFT filtered clicks which are correlated across channels to estimate time differences of arrival (TDOAs) which are fed into standard 3D hyperbolic localization algorithms. M3R requires multiple computers to get real-time results, likely due to the use of FFT and the classification processes. When spectrogram analyses are used for classification [7], FFT generates permutations in each frequency bin [8], which might result in severe performance degradation for transient signals. Moreover, the spectrogram method is limited in the case of non-linear time–frequency analysis [9]. Some monitoring models have been developed using both time and frequency–domain click and whistle vocalization analyses [4]. But TD analyses are sufficient for tracking if the problem of classification is not addressed; it is then assumed that all transient detections are real clicks or echoes. For example, in [10] the foraging depth of sperm whales is estimated by a TD localization using only one hydrophone at an unknown depth. This algorithm is quite fast, but cannot generate 3D tracks. Nosal and Frazer [11] proposed a method that relies exclusively on TDOAs between direct and reflected paths (BELLHOP

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