The effects of a shallow-water acoustic channel on Right whale vocalisations

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For mitigation and monitoring of Right whales, identifying their presence from their vocalisations is a key research issue. Their vocalisations are characterized as frequency modulated up-sweeps with duration of ~1s and a frequency range from 50Hz to 200Hz. Acoustic methods to classify these received calls are assessed by the variation in the received data set. As well as the natural variation in vocalisation within the species, the received acoustic signals are also influenced by the effect of the acoustic channel. The shallow water of Cape Cod Bay is one of the favoured habitats for the Northern Right whale. Such waters act as an acoustic waveguide where multiple reflections off boundaries cause calls to become dispersive in nature. In this paper we discuss the effects of channel environmental parameters such as water depth and sediment type on firstly the FM deviation and secondly on the time difference of arrival between the first and second modes, which in turn influences acoustic range estimation. Such channel effects were studied using the normal mode acoustic propagation model (PROSIM). An analysis of real acoustic data recorded in Cape Cod Bay (2001 obtained from IFAW) will be also presented in terms of dispersion results.

1 Introduction

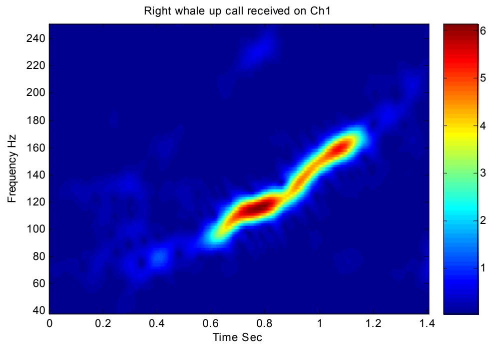
Right whales are an endangered species [5]. Like many marine mammals that use underwater sound for communications [13], the Right whale produces distinctive vocalisations. Common calls are characterized as frequency up-sweeps having a typical duration of about 1s and a frequency range from 50Hz to 200Hz [1].

In deep water environments such vocalisations are recorded as true signals with little channel distortion. However, the Right whale feeding grounds are often in shallow water areas [9]. Such shallow water acoustic environments act as waveguides with multiple reflections off the sea surface and the sea bottom resulting in multipath effects. A primary effect of such multiple paths is to cause distortion on the whale vocalisations received at the hydrophones due to this channel dispersion effect. In the literature, the existence of dispersive Right whale up calls was reported [7] and can be used to estimate the acoustic range to the vocalising whale from the receiver [12].

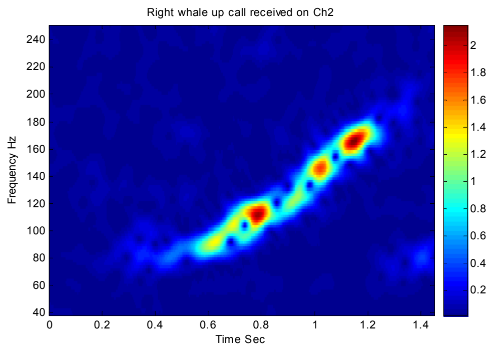
For purposes of Right whale vocalization classification, a variation in the recorded data set induced by the channel will affect the performance of any suggested classifier [14]. In order to design a robust classifier, it is thus important to better understand the channel distortion effects and in particular be able to quantify the impact of environmental parameters, including the sea bottom type and water depth on the propagating signal.

In order to illustrate the dispersion effects of a shallow water channel, consider Fig. 1 that shows three Right whale up-swept calls emitted by the same source and received at three recording channels (refer to the configuration of the receivers in Fig. 2). Fig. 1(a) shows a non-dispersive typical up-sweep received at Ch1 (assumed to be the closest receiver to the vocalising whale) while Fig. 1(b) and Fig. 1(c) display the effect of the dispersive shallow channel on two signals received at further recording channels (Ch0 and Ch 2).

In all spectrograms displayed in this paper, the relative intensity of the spectrograms is indicated by the colour bar.



(a)



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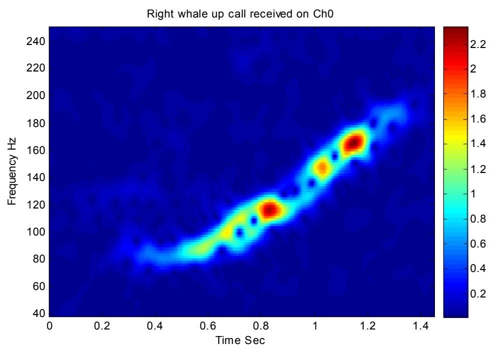


(c)

Fig. 1 Spectrograms of Right whale up-swept calls recorded in 30m deep shallow water of Cape Cod Bay (IFAW). (a) Shows a non-dispersive call; (b) and (c) illustrate the dispersion effects.

2 Cape Cod Bay Data

The experimental data used in this work was obtained from the International Fund for Animal Welfare (IFAW) and relates to signals recorded by triangularly configured hydrophones moored some 2m from the seafloor in Cape Cod Bay, on the Eastern Coast of the USA (March 2001), as shown in Fig. 2.

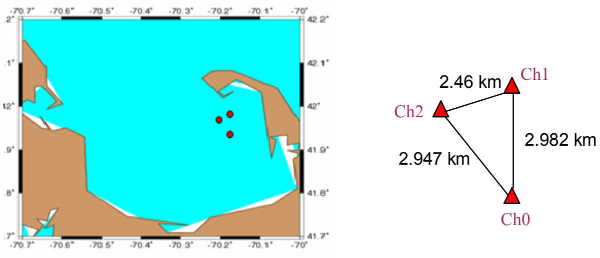


Fig. 2 Locations and configuration of the three recording channels in Cape Cod Bay. Image Courtesy of [10].

Cape Cod Bay is a semi-enclosed embayment with the seafloor varying in depth from 30m to 60m from south to north [3]. In this paper we consider the bottom as essentially flat (30m depth) and the environment horizontally stratified. The sound speed profile is assumed constant at 1463m/s [10].

The sea bottom type differs between the shallow margins and deep basin of the bay due to the distribution of sedimentary deposition in the bay. In water depths of less than 30m, the sub bottom consists of bedrock, glacial drift and sediments ranging from boulder field to gravelly coarse to medium sands. In water depths ranging from 30m to 60m, there is a covering of mud and muddy fine-to-very fine sands over the basin floor [3].

Visual scanning of spectrograms (Fig. 1) of the recorded acoustic data reveals the existence of dispersive impacts caused by the acoustic channel in Cape Cod Bay.

3 Dispersion in a shallow water channel

In uniform shallow waters, the environment acts as a waveguide through which an acoustic signal becomes trapped and propagates for long ranges due to reflections off the sea surface and the sea bottom (see Fig. 3). Such multipath propagation causes the signal to become dispersive at the receiver.

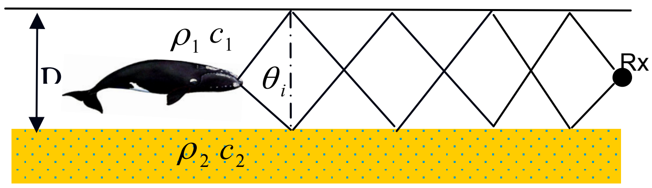


Fig. 3 The waveguide traps propagating waves in shallow water. D is the water depth; ρ_1, c_1 and ρ_2, c_2 are the sound velocity and density of water and sediment respectively; and θ_i represents incident angles.

The term "dispersion" as a phenomenon occurring in waveguide, refers to the dependence of the mode's group velocity on its frequency [8]. By plotting the group velocity against frequency for every propagating mode, dispersion curves are produced [4]. For the particular case of a 30m shallow water depth and muddy-sand sediment, typical of the Cape Cod Bay experimental site, the following dispersion curves (Fig. 4) can be derived for the first four modes [4].

Fig. 4 illustrates two aspects of dispersion: intermodal dispersion and intramodal dispersion [14]. While the former supports earlier arrival of lower modes than that of higher ones, the latter shows how higher frequencies within the same mode propagate faster than lower frequencies.

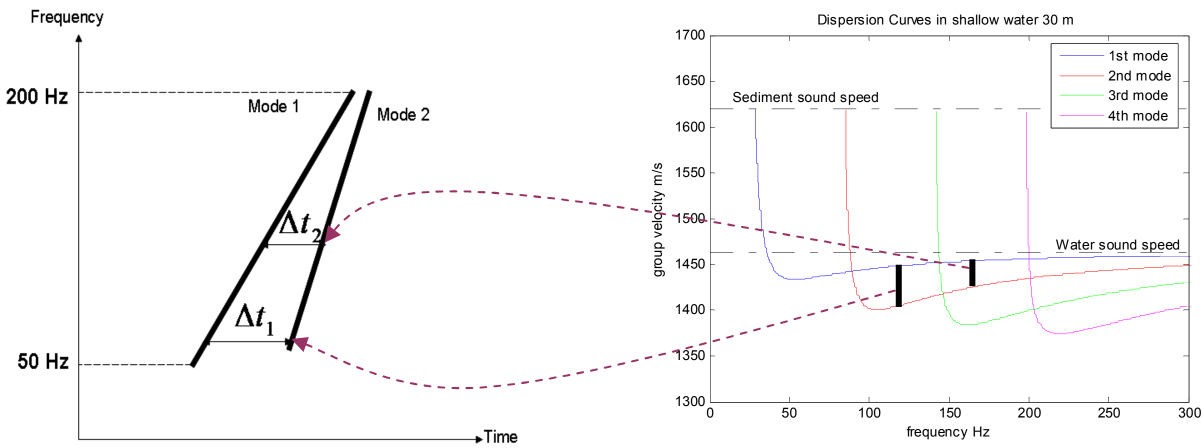


Fig. 4 Dispersion curves for a 30m water depth and muddy sand sediment. Black bars indicate that the time difference of arrival between modes at different frequencies is a function of their group velocity difference.

Within the time-frequency representation of a dispersive received signal, an aspect of intermodal dispersion can be recognized as multiple arrivals of the transmitted signal. This can be illustrated in Fig. 5. The dispersion curves provide information about the number of modes that can propagate through the channel at a specific acoustic frequency. For instance, at a frequency of 120Hz, only two modes can propagate. This can be seen in Fig. 5 where it was assumed that all likely modes arrive at the receiver.

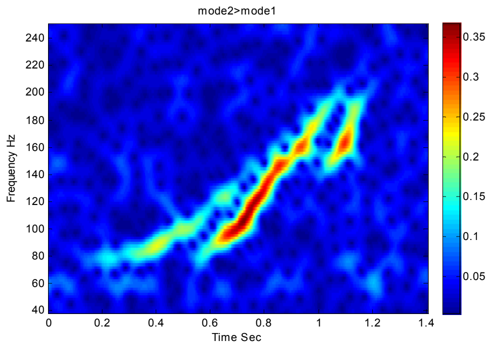


Fig. 5 An up-swept dispersive vocalisation showing three mode arrivals in Cape Cod Bay data

Propagating modes can also be considered as standing waves in the depth direction [6]. Every mode has zero crossings (nodes) and its opposites (anti-nodes) along the depth axis. Four modes are likely to propagate at 200Hz through the acoustic channel characterized by the dispersion curves shown in Fig. 4. The dependence of the excitation of the modes on depth for 30m deep water channel is plotted in Fig. 6 [4].

The depths of both the source and the receiver control the mode excitation [7, 12]. Since the receiver depth is known in the Cape Cod Bay experiments, we will focus on the influence of the source depth. For example, Fig. 6 indicates that if we had a source at a depth of 17m depth the first and third modes would be highly excited, whereas the second and fourth modes would not be excited. No modes are excited at the sea surface.

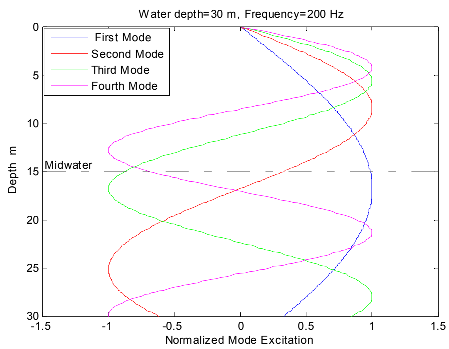


Fig. 6 Mode excitation as a function of water depth. At 17m depth, the first and the third modes are excited while the second and the fourth are not.

One implication of the above theory is that by studying the relative excitation of the first and second modes in the dispersive channel we will be able to assess the likely depth of the source. For example, if the first mode is more excited than the second one, the whale is likely to be located at mid water; or alternatively close to either the sea surface or the sea bottom. To illustrate this concept, Fig. 7 and Fig. 5 show two dispersion effects where mode 1 and then mode 2 dominates respectively.

In Fig. 7, the first mode is more excited than the second one therefore; the calling whale is expected to be located at mid water. In Fig. 5, the second mode of the received signal is more excited than the first one. This suggests that the vocalising whale may be close either to the sea floor or to the sea surface.

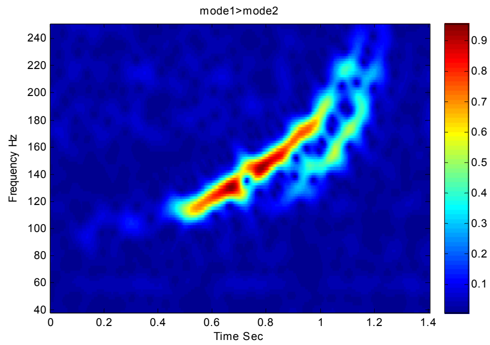


Fig. 7 Spectrogram of a dispersive recorded up call. It illustrates how mode intensity is excited according to the source depth.

4 Normal mode modelling

In order to investigate if and how the sea bottom type and water depth influence the dispersion effects, we followed up our analysis of the real data with a modelling exercise using the PROSIM normal mode model. The experimental parameters used in the model were all derived from the Cape Cod Bay scenario. PROSIM is a broadband layered normal mode model method for adiabatic broadband sound propagation based on the range-independent model called ORCA [2]. The simulated transmitted signal was a linear FM chirp as defined earlier in the paper. The source level was set to the average value of 150 dB re 1μPa as measured for the North Atlantic Right whale [11]. Sound production was assumed to be omni-directional in the forward direction.The environmental parameters used in the model are summarized in Table 1. The compressional wave attenuation coefficient was assumed to be negligible in this work.

The primary effect of increasing water depth is to decrease the mode's cut-off frequency below which signal energy can not propagate through the channel. Such an effect controls the number of propagating modes and the mode's group velocity which consequently affects the FM deviation of the first mode as well as the Time Difference Of Arrival (TDOA) between the first two modes.

Layer	water	Muddy sand	Gravelly sand
Sound velocity m/s	1463	1620	1875
Density kg/m^3	1026	1373	2289

Table 1 Environment parameters used in PROSIM model

4.1 The effect of water depth on the first mode

Since the first mode would be considered for classification purposes, the effect of water depth on the first mode was investigated by transmitting a linear chirp through three channel scenarios having the same sediment type namely gravelly sand but with different water depths 30m, 45m, and 60m. The range is taken as 15Km. In figure 8, the first mode propagating through a 60m deep channel arrives earlier than those traveling through 45m and 30m deep waters.

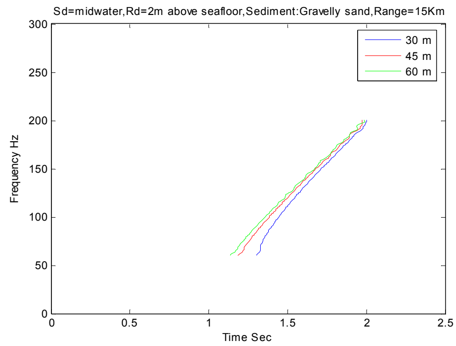
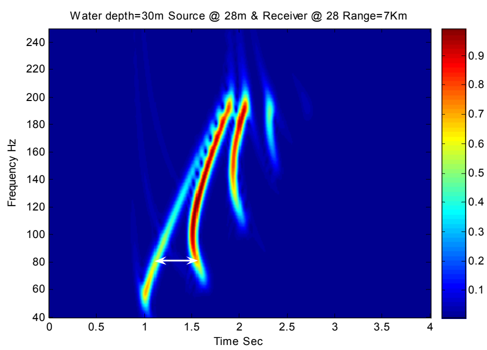


Fig. 8 Frequency contours of the first mode for different water depths. The source depth which is assumed to be at mid water is 15Km from the receiver. Note how the first mode propagating in 30m deep water is the slowest mode.

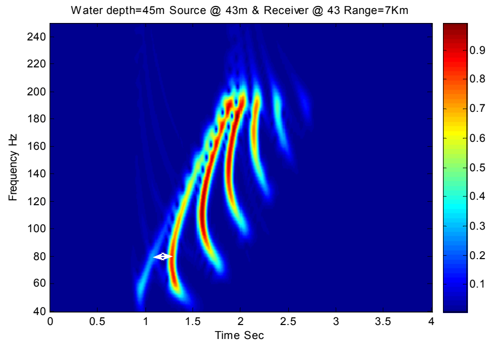
To ensure a clear frequency contour of the first mode, the source was assumed to be located at mid water.

4.2 The effect of water depth on the TDOA between modes

Results for two water depths 30m and 45m with the same sediment of gravelly sand are shown in Figure 9. While 45m deep water supports more propagating modes, the TDOA between the first two modes in 30m deep water is bigger than that in 45m deep channel as indicated by the white horizontal arrows drawn at 80Hz.



(a) 30m deep water



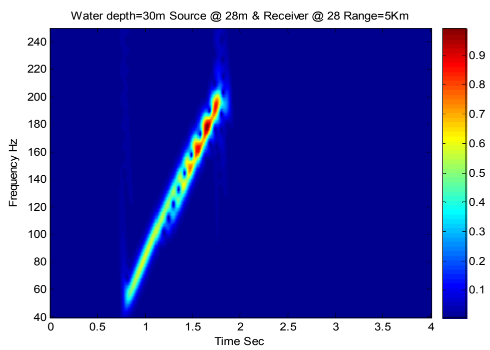
(b) 45m deep water

Fig. 9 Spectrograms of two dispersive up-swept calls for different water depths and the same sea bottom. Note that TDOA in 45m water is smaller than that in 30m deep water.

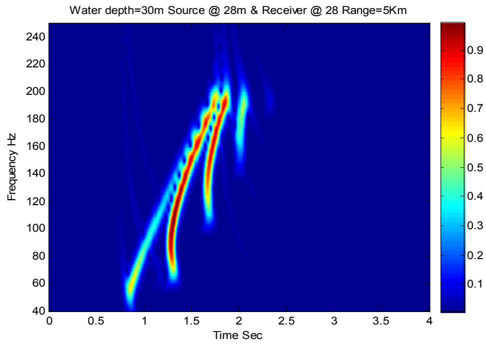
4.3 The effect of bottom type on dispersive up calls

The influence of the sea bottom on the dispersive received up calls can be addressed in terms of the acoustic impedance of the sediments. Sediments of higher acoustic impedance support lower cut-off frequencies which in turn lead to a larger number of propagating modes. In contrast with the water depth effect, decreasing the cut-off frequency in this case results in bigger TDOA between the first two modes.

Results for two different bottom types are shown in Fig. 10. The water depth and range for both results are 30m and 5km respectively. Fig. 10 shows that the linear chirp signal propagating over sediment of gravelly muddy sand has a bigger TDOA between the first and second modes than that travelling over sediments of muddy sand at low frequencies, say 100Hz. The influence of bottom type on the TDOA between the first two modes was noticeable in very shallow waters (≤60m) at low frequencies. The effect of sediment types in deeper environments (≥60m) was found to be negligible for Right whale up-swept calls. This emphasizes the importance of the sediment type at shallow water depths.



(a) Muddy sand



(b) Gravelly sand

Fig. 10 Spectrograms of received signals at 5km in 30m deep water for two sediment types. (a) Muddy sand: less modes and smaller TDOA (b) Gravelly sand: more modes and bigger TDOA

5 Conclusion

In this paper, we have explored the North Atlantic Right whale vocalisations received in a dispersive shallow water channel. The dispersion effects were noted in experimental data from Cape Cod Bay. In our Normal Mode Modelling, we have confirmed that both the water depth and the sediment bottom type influence the dispersive received up calls. While the number of propagating modes increases with increasing water depth or the acoustic impedance the sea bottom, these parameters have a contrasting effects on the mode's group velocity which in turn affects the TDOA between the first two modes. This work further develops research reported by [12] where the influence of environment parameters on the received up calls increases with the range of the calling whale to the receiver.

Work on the effects of dispersive shallow waters will be incorporated into development of a robust Right whale classifier.

Acknowledgments

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