A Possible Relationship Between Waveguide Properties and Bandwidth Utilization in Humpback Whales

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Abstract-**Humpback whales may use different sounds based on the propagation characteristics of the environment within which they are vocalizing. We used computational techniques to assess how well different frequencies propagate in environments frequented by humpback whales. The results of these simulations suggest that humpbacks should use different frequencies in northern feeding grounds from those they use in southern breeding areas in order to achieve maximal propagation ranges in both regions. Preliminary data from previous reports suggest that humpback whales do use different frequencies in these different environments, consistent with the predictions of our simulations.**

I. INTRODUCTION

Over the past fifty years, ocean acousticians and engineers have made good use of the unique propagation characteristics of oceanic environments. Humpback whales (*Megaptera novaeangliae*), in contrast, have enjoyed 30 million years of selection in adapting their use of sound to the marine environment. Consideration of the acoustic abilities of humpbacks can thus potentially lead to novel insights about how sound might best be used in the ocean.

Humpback whales are highly vocal, producing a wide variety of sounds [1-2]. Current data suggest that spectrotemporal features of humpback sounds are correlated with the time of year, and location in which they are produced. During the summer, when whales are at higher latitudes, they tend to produce short duration, low frequency sounds in unstructured sequences [3]. In the winter, when whales are at lower latitudes, they typically produce longer duration, higher frequency sounds [4-5]. Winter sounds are often produced in long stereotyped sequences that have been described as songs [6].

Current explanations for why humpbacks modify acoustic properties of their sounds over time are primarily based on their presumed functions [7-8]. Humpbacks are mainly occupied with feeding during the summer, and breeding during the winter; vocal variation is believed to stem from these behavioral differences. Humpback whales surely vary the sounds they produce so that the sounds are well suited for their intended functions. However, the extent to which humpbacks can control where and how their sounds propagate is strongly constrained by the properties of the environment in which they produce the sounds. Environmental features thus can play a large role in determining what sounds will be useful for a particular purpose.

Preliminary results in the literature suggest that maximal propagation ranges in the North Atlantic are typically reduced in the summer relative to the winter, and that lower frequency bands are required in the summer to achieve maximal ranges [9]. Humpback whales must contend with large variability in propagation characteristics because many individuals migrate thousands of kilometers annually. If minimizing transmission loss is an important factor in humpback whales' use of sound, then humpbacks can benefit from modulating the spectral and energetic properties of their sounds as they move between different regions. We hypothesize that humpback whales vary the frequencies they use to account for the attenuating effects of the environment within which they are vocalizing.

In the current study, we use normal mode computations to examine how properties of environments inhabited by humpback whales constrain propagation of the sounds they produce. Previous simulations suggest that the frequency band used by humpback whales in the winter tends to be lower than that needed for maximum propagation ranges [10]. The current simulations extend these analyses to summer environments of humpback whales. These regions include shallow-water channels with sound speed profiles and bottom properties that are substantially different from those encountered by humpback whales during the winter.

II. METHODS

A. Propagation Model

The computations in this paper used Westwood *et al.*'s [11-12] normal-mode model, ORCA. ORCA can be used to estimate how sounds of various frequencies attenuate as they propagate in an ocean channel with a multi-layered bottom. Because ORCA is a plane-layered, range-independent model, it does not account for effects of scattering due to variability in water depth, bottom properties, and sea state. Scattering typically increases transmission loss.

B. Simulated Environment

During the summer, humpbacks are commonly observed feeding in the coastal waters of the North Pacific. We used the environmental parameters of [13-14] to approximate one type of environment humpback whales would likely encounter in their summer habitats (see Table 1 for details). These parameters are based on measurements made in Haro Strait, British Columbia, during the summer. Although humpback whales are seldom seen in Haro Strait today, they did frequent this area in the past (P. Miller, personal communication). Several acoustic propagation studies have recently been conducted in Haro Strait that may be useful for assessing the accuracy of our simulations. As shown in Figure 1, the sound speed profile in Haro Strait is essentially an isovelocity profile (very little variation was reported in [14]). The bottom in this environment is modeled with a layer of silt and sand over a second layer of sand [14].

TABLE I
ORCA INPUT FILE FOR FULL GEOACOUSTIC MODEL

(1) Defines the physical properties of the upper boundary of the sound channel (air) and (4) defines the lower boundary (sediment). cp=compressional speed in m/s, cs=shear speed in m/s, rho =density in g/cm^3, ap=compressional wave attenuation, as=shear wave attenuation, z=depth in m, nsvp=number of sound-speed profile points in the ocean, ctol=tolerance used in fitting the sound-speed profile to eliminate layers (ctol=0 keeps all layers), nbot=number of layers in the ocean bottom, ii=type of compressional speed profile (ii=1 is linear), h=layer thickness, cs1=compressional speed at the top of layer 1, cs2=compressional speed at the bottom of layer 1 (similarly for rho1, rho2; ap1, ap2; and as1, as2).

(1) For upper halfspace: cp=350, cs=0.0, rho=0.00121, ap=0.0, as=0.0
(2) Ocean profile: nsvp=2, ctol=0, z=0, cp=1482.5, rho=1.05, ap=0; z=60, cp=1482.6
(3) Bottom profile: nbot=1, ii=1, h=45, cp1=1560 , cp2=1560 , cs1=80 , cs2=80 , rho1=1.7, rho2=1.7, ap1=-.03, ap2=-.03, as1=0, as2=0
(4) For lower halfspace: cp=2000, cs=400, rho=1.9, ap=-.03, as=0

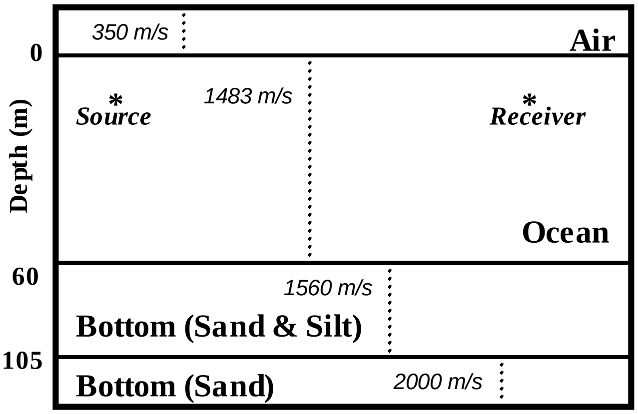

Fig. 1. Example sound speed profile for ORCA simulations. Solid lines show boundaries between channels and dotted lines show how sound speed changes as a function of depth and material.

C. Procedure

We define optimum frequency as the frequency that achieves the maximum propagation range, given a particular environment and source depth. Analyses of how environmental parameters affected optimum frequencies were directly comparable to those performed in [10]. Effects of the following parameters were investigated: water depth, source depth, and receiver depth. Water depths of 20, 40, 60, 100, 200, and 350 m were simulated. Source depths of 5, 15, and 30 m were chosen based on past reports of humpback whale dive depths in summer habitats [15]. Optimum frequencies were calculated for several scenarios using continuous wave techniques. Computations were performed for 20 frequencies evenly spaced between 20 to 4000 Hz. For each frequency, transmission loss (TL) was calculated at 10,000 receiver positions. Receiver positions were located at 200 ranges from the source (evenly spaced between 50 to 60,000 m), and at 50 depths (evenly spaced between the surface and bottom), resulting in a 50X200 matrix of TL values. A logarithmic curve of the form TL = $a\log r$ was fit to each row of the matrix (corresponding to each water depth) to estimate depth-dependent TL curves. The optimum frequency (f_o) and receiver depth (r_o) for a particular environment were calculated by finding the TL curve with the minimum "a" value (a_m) across all simulations in that environment.

Correlations between parameters and optimum frequencies were measured using the Pearson correlation coefficient (r). Optimum frequencies calculated in the current study were compared with those calculated for Hawaiian environments (as reported in [10]) using paired t-tests. (Optimum frequencies for Hawaiian environments with a thermocline starting at 70 m were excluded from these comparisons so that the number of optimum frequencies calculated at each water depth were the same for winter and summer simulations).

III. RESULTS

A. Optimum Frequencies

Table II summarizes the simulation results using normal modes to model sound propagation in the Haro Strait summer environment. In this table, we present the calculated optimum frequencies along with the corresponding water and source depths, optimum receiver depths, and information on parameter a.

Optimum frequencies across all simulations ranged between 20-3160 Hz. Transmission loss varied little across frequencies for all water depths (mean of standard deviation measures across depth = 0.4±0.3). Nevertheless, the variability of transmission loss as a function of frequency (estimated by σ_a) appeared to decrease with increasing source depth (r = -0.75) and water depth (r = -0.33). Changes in water depth did not appear to strongly determine the optimum frequency in summer environments (r = -0.19). Source depth was a better predictor of optimum frequencies (r = -0.45).

TABLE II
OPTIMUM FREQUENCIES FOR HUMPBACK SUMMER ENVIRONMENTS
d_w = water depth, d_s = source depth, f_o = optimum frequency, r_o = optimum depth, $a_m = \min_i[a_i]\log r$; $\bar{a}$ and σ_a are the mean/standard deviation for all a_i.

d_w (m)	d_s (m)	f_o (Hz)	r_o (m)	a_m	$\bar{a}$	σ_a
20	5	3160	4.9	14.3	14.8	1.2
	15	230	12.6	14.2	14.7	0.7
40	5	1280	36.0	14.8	15.2	0.7
	15	230	22.5	14.8	15.0	0.3
	30	230	22.5	14.8	15.0	0.1
60	5	440	57.6	15.1	15.4	0.7
	15	1700	45.6	15.1	15.3	0.2
	30	20	52.8	14.9	15.1	0.1
100	5	440	98.0	15.4	15.8	0.7
	15	2950	15.1	15.5	15.6	0.2
	30	230	31.3	15.5	15.7	0.1
200	5	1280	196.0	16.0	16.3	0.6
	15	440	187.9	16.1	16.3	0.1
	30	20	41.6	15.8	16.2	0.1
350	5	230	8.1	16.6	16.9	0.5
	15	1490	335.8	16.4	16.7	0.1
	30	20	93.7	16.1	16.7	0.2

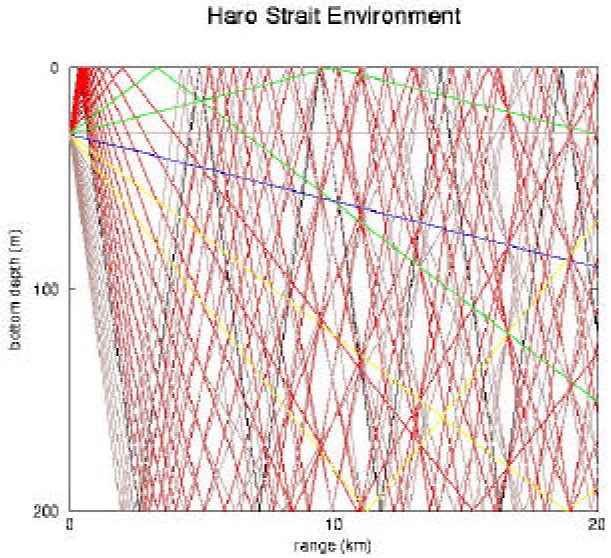

Fig 2. Ray trace for a summer environment; 30 m source depth. Note how intersections of rays are evenly distributed across the water column.

B. *Comparisons with Previous Results*

The mean optimum frequency calculated for summer environments (847±992 Hz) was significantly lower ($p < 0.01$) than that reported in [10] for winter environments (2420±1400 Hz). The minimum optimum frequency in summer environments (20 Hz) was also much lower than that calculated for winter environments (650 Hz). Overall, calculated transmission losses were significantly lower ($p < 0.01$) in summer environments (mean a_i = 15.7±0.7) than in winter environments (mean a_i = 17.4±1.5). Variability in transmission loss across different frequencies and depths was also significantly lower ($p < 0.01$) in summer environments.

Whereas source depth was closely correlated with optimal receiver depth in simulated Hawaiian environments ($r = 0.96$), source and optimum receiver depth were not positively correlated in simulated summer environments ($r = -0.10$). The mean optimum receiver depth (74.2±88.3 m) was significantly deeper ($p < 0.01$) in summer environments than in winter environments (14.5±7.4). Figures 2 and 3 illustrate propagation characteristics in summer and winter environments that may account for these differences in optimum receiver depths.

IV. DISCUSSION

Our simulations predict that optimum frequencies in winter environments of humpback whales are higher than optimum frequencies in their summer environments, and that sound transmission is less constrained by channel properties in the summer than it is in the winter. These results immediately raise two questions:

(1) Do these simulations adequately characterize environmental constraints encountered by vocalizing humpback whales?

(2) Do humpback whales use higher frequencies in winter environments and lower frequencies in summer environments?

We address these issues in the following sections.

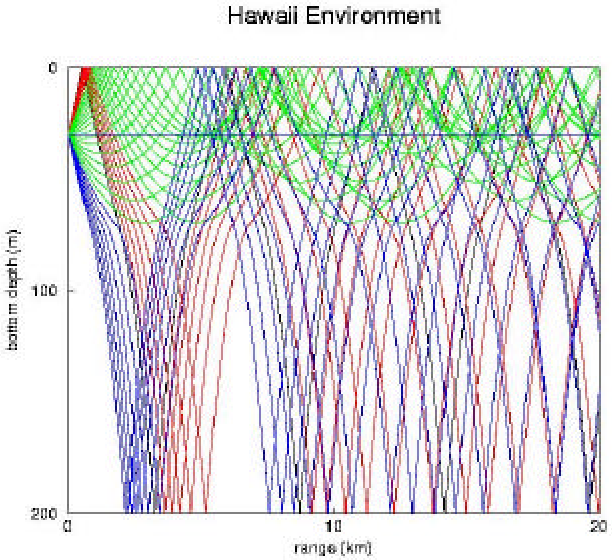

Fig 3. Ray trace for a winter environment; 30 m source depth. Note how rays are focused within a surface channel.

A. *Accuracy of Simulations*

Simulations cannot replicate propagation in the real world, but they can bring to light issues which might not otherwise be considered and provide a quantitative framework within which such issues can be investigated [16]. Some factors that were not considered in our simulations, but that could impact computations of optimum frequency, are bathymetric variations (which are significant in Haro Strait), possible multi-layered structures of the sea bottom, and effects of surface fresh water/ice [15]. Additionally, these simulations only characterize a subset of the habitats where humpback whales are likely to vocalize during the summer. Past studies have generally found that simulations based on normal-mode theory provide good approximations to real-world situations [9,17]. Data collected from recent acoustic propagation experiments conducted in Haro Strait may be useful in assessing the accuracy of our results.

The precision of our simulations is perhaps less important than the information they provide regarding possible differences between the propagation characteristics of winter and summer habitats of humpback whales. In particular, transmission loss appears to vary less as a function of frequency in summer environments. A few cases in Table I show an optimum frequency of 20 Hz. In these cases, although the listed value was found to be optimum, transmission loss varied only slightly with frequency. Humpback whales producing higher frequency sounds in these environments would thus achieve comparable propagation ranges.

In addition to differences in optimum frequencies, other differences were observed between simulated Hawaiian and Haro Strait environments. In Hawaiian environments, optimum receiver depths were comparable to source depths; for source depths between 5 and 30 m, optimum receiver depths were found to vary roughly between 7 and 29.5 m. In the Haro Strait case, most optimal receiver depths were between 5 and 60 m (a finding compatible with reports in the literature on the preferred depths of humpbacks in their summer environment [15]). A few optimum receiver depths deviated from this general trend and were found to be close to the water-sediment interface.

The ray traces shown in Fig. 2 and Fig. 3 explain the differences in optimum receiver depths for the two environments. The sound energy is mostly concentrated in the first 50 m of the water column for the Hawaiian environment (Fig. 3), explaining why optimum receiver depths are shallow. The sound energy appears to be evenly distributed in the water column for Haro Strait, explaining optimum receivers found at deeper depths. Looking at Figure 3, one can also understand why bottom depth had little effect on optimum frequency calculations in Hawaiian environments; most of the rays do not reach the bottom of the waveguide.

Interestingly, water depth did not appear to be a major factor for optimum frequency determination in the Haro Strait simulations. A strong correlation between water depth and frequency had, however, been reported in [9] for a sound speed profile similar to that of Figure 1. It should be noted that source and receiver depths were fixed in [9], whereas they were varied in our simulations. Also, the geoacoustic properties of the bottom used in [9] differed from those shown in Figure 1. Because of these differences, the results of the two studies are not directly comparable. Further work will consider differences between theses two simulation studies to address how variability in bottom properties and sound speed profiles affects optimum frequency calculations.

B. *Humpback Whale Vocal Behavior*

Although little is known about the sounds humpback whales produce in the summer, current data suggests that humpbacks predominantly use low frequency, short duration sounds during this time. Thompson et al. [3] described a variety of "moans" and "grunts" produced by humpbacks off the coast of Alaska. Moans had a median upper frequency limit of 385 Hz and a median duration of 0.8 s. The median upper limit for grunts was 510 Hz with a median duration of 0.2 s. The most frequent (and highest amplitude) sounds observed were 0.3-0.4 s "pulses" with frequencies between 25-80 Hz. Similar moans and grunts, with mean fundamental frequencies between 53 and 70 Hz, were produced by two entrapped humpback whales in Newfoundland [18]. These whales also occasionally produced short duration sounds (0.01-0.2 s) containing frequencies between 1250-3700 Hz (described as "chirps," "cries," and "clicks"). During feeding bouts, humpback whales produce tonal signals with fundamental frequencies between 440-600 Hz [19-21].

Humpback whale "songs" produced on feeding grounds are generally shorter in duration than songs produced in the winter [22-24]. The spectral properties of sounds within feeding ground songs have not been described. Subjective comparisons of sounds used by humpback whales in the summer to those used in the winter suggest that whales use frequencies between 500-4000 Hz more extensively in the winter, independent of social context [18,25]. Humpbacks seldom produce sounds with significant energy below 100 Hz in the winter [26].

The limited data currently available suggest that humpback whales do predominantly use lower frequencies in summer environments and higher frequencies in winter environments. Such bandwidth utilization is consistent with what normal-mode theory predicts is necessary to achieve maximal propagation ranges, suggesting that humpback whales are modulating the acoustic properties of their sounds to account for environmental constraints. However, past descriptions of humpback whale vocalizations only provide a rough sketch of how humpbacks utilize different frequency bands. Measurements of how much time and energy humpback whales spend producing particular frequencies in different locales are clearly needed to adequately assess our hypothesis.

In the past, researchers studying possible environmental effects on sound transmission by humpback whales (and other marine mammals) have focused on possible interference from noise sources [27-32]. Some evidence has been found that humpback whales change the sounds they produce in response to such interference [28,30]. It is difficult to interpret such changes, however, without understanding how physical features of the ocean have shaped in the past, and constrain in the present, the acoustic properties of humpback whale vocalizations. The effects of noise sources on humpback vocal behavior may be strongly dependent on the properties of the environment within which the noise occurs, especially if humpbacks are producing sounds that are "designed" to match the propagation characteristics of particular environments.

Humpback whales may be able to transmit sounds effectively without modulating properties of their sounds to account for channel characteristics. This would be feasible if either the sounds only needed to travel short distances, or if whales used signals that covered a wide range of frequencies. Whether humpback whales dynamically adapt the sounds they use to account for environmental constraints or use a fixed band of frequencies is a question that can be readily addressed through empirical observations.

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