

Active High Frequency Phased-Array Sonar for Whale Shipstrike Avoidance: Target Strength Measurements

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Abstract—Ship-strike is a major cause of death for large whales. For the northern right whale (*Eubalaena glacialis*) ship-strike is the leading cause of documented deaths. Forward-looking sonar provides one possible solution to this problem. A forward-looking sonar could provide information to the ship operator about the presence and location of large whales ahead of a vessel. This paper documents two sea tests in which target strength data was collected for humpbacks (*Megaptera novaeangliae*) and for northern right whales. Results are compared to previously published whale target strengths. Blubber thickness and frequency are used in a reflection coefficient model to explain the differences between the previous results and those presented in this paper.

I. INTRODUCTION

Ship-strike is a major cause of death for large whales. For the northern right whale (*Eubalaena glacialis*) ship-strike is the leading cause of documented deaths. Forward-looking sonar provides one possible solution to this problem. A forward-looking sonar could provide information to the ship operator about the presence and location of large whales ahead of a vessel. The application of the sonar on the bow of a vessel is a old problem solved many times for mines, submarines, etc. The difference with whales is that performance modeling and system design requires information on the target strength of the whales. This paper documents two sea tests in which target strength data was collected for humpbacks (*Megaptera novaeangliae*) and for northern right whales.

An important contribution was made by Love [1] who measured the target strength of humpback whales off a tower in the Florida Straits at 20 kHz. He found that the target strength of an adult humpback 15 meters of length varied from 7 dB broadside and -4 dB head on. While this work was likely not intended to support the concept of whale avoidance using a forward-looking sonar, it provides an important milestone.

II. SYSTEM DESCRIPTION

The system used in the study consisted of a cylindrical transmit array and planar receive array. All the transmit elements were driven in parallel with a 86.25 kHz CW pulse with a duration of 3 ms and having a source level of 170 dB. The circular array of radius 20 cm provided a horizontal beamwidth of 90 degrees and a vertical beamwidth of 120

degrees. The receive array consisted of 64 elements in an 8x8 checkerboard pattern with 1/2 wavelength spacing in the vertical and horizontal.

III. TARGET STRENGTH MEASUREMENTS

Two sea tests were conducted to validate the concept of whale avoidance with a forward-looking sonar. The first was conducted in May, 1998 on Stellwagon Bank in which a humpback whale was imaged. The second was conducted in December, 1998 in Cape Cod Bay in which northern right whales were imaged.

An example of the results from the May, 1998 test is shown in Fig. 1 for a 15 m humpback whale at broadside. The plot is a vertical slice of the acoustic data. Time-varying gain was applied to the data. In Fig. 2, a PPI (Plan-Position-Indication) plot is shown of the same data.

Target strength for the whale was measured to be 4 dB broadside. This is slightly lower than the 7 dB in Love's results. A possible explanation for the difference is provided below.

In December, 1998, the same system was used to image three northern right whales and an example of the results are shown in Fig. 3 in a "cylindrical scan" display. The acoustic size of the whale is much larger than the actual size because of the large beamwidth of the receive array.

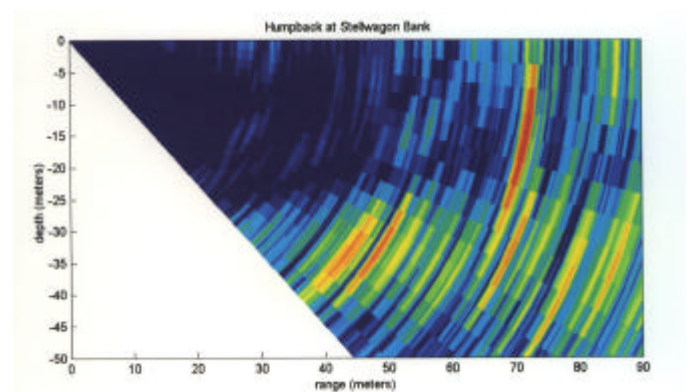


Fig. 1. Results from May, 1998 test of the AWARE system in which a humpback whale was imaged along with the seafloor. Color indicates intensity of the return in dB with a range of 25 dB between the blue and red.

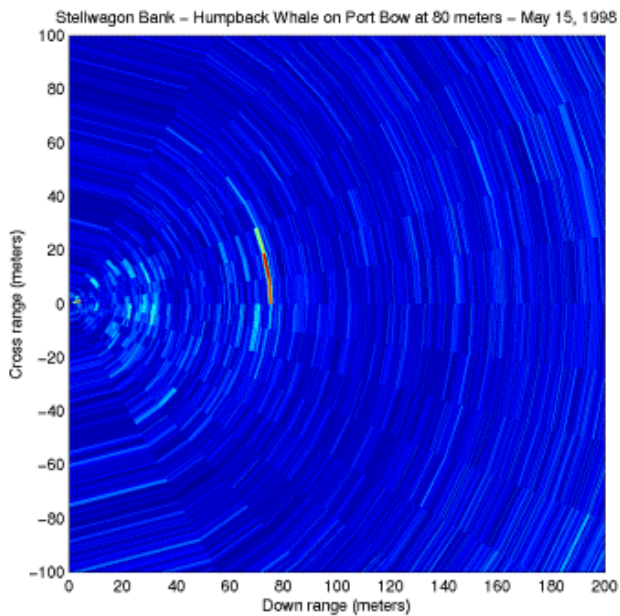


Fig. 2. PPI display of 15 m humpback whale in the May, 1998 test. The humpback whale is indicated by the red feature at a range of 80 meters. The color indicates intensity of the return in dB with a range of 25 dB between blue and red.

Table I summarizes the results of the target strength measurements of the three right whales. Whale 1 was an adult of length of 13 meters. Whale 2 was an adult of length of 15 meters. Whale 3 was a juvenile of length 8 meters missing the right half of its tail fluke. Note that the target strength estimates have been corrected for near field effects and should be valid in the far-field. In Table I, aspect angle refers to the angle with the whale makes to the sonar, i.e. 0 deg is head on, 90 deg is broadside with whale’s head to port, 270 deg is broadside with whale’s head to starboard, and 180 deg is tail on.

Note that the target strength estimates have been corrected for near field effects and should be valid in the far-field. The data show that size and aspect angle play understandable roles in the target strength. The maximum broadside target strength for the right whales is about -1 dB. The results show that the target strength of the northern right whale may be 5 dB less than that of a humpback whale of similar size at our frequency of 86 kHz.

One possible explanation for the differences between the humpback whale and the right whale is the presence of a thick blubber layer on the right whale. Blubber makes up about 43% of total body weight of the right whale and only 25% of the humpback whale.[2] This increased blubber and the fact that our frequency was 86 kHz and Love’s was 20 kHz may explain the differences in the data sets.

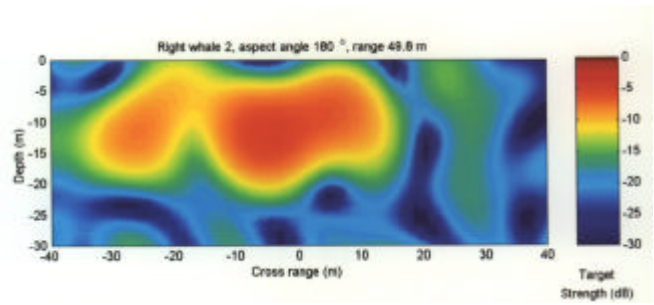


Fig. 3. Example of the results from the December, 1998 test involving northern right whales. The range to the animal is about 50 meters and the water depth is approximately 40 meters. The colors indicate far-field target strength.

A simple way to test the hypothesis that blubber thickness and acoustic frequency are important factors in target strength is to compute the plane wave reflection coefficient from a 3-layer “infinite” whale. The three layers are the water, blubber, and air from the whale’s lung. (This assumes that the lung is the major reflector but the concept can be applied to bone structure with similar results.) The 3-layers are depicted in Fig. 4. An attenuation factor can be introduced into layer 2, the blubber layer.

TABLE I

SUMMARY OF TARGET STRENGTH MEASUREMENTS MADE IN DECEMBER, 1998 OF THREE NORTHERN RIGHT WHALES

Whale I.D.	Range (m)	Aspect (deg)	Far-field TS
1	84	225	-2.1
1	60	225	-1.4
1	48	225	-4.8
1	54	225	-4.4
1	54	225	-1.9
2	49	135	-2.3
2	50	180	-4.3
2	47	180	-5.3
2	46	180	-6.6
2	68	250	-2.7
2	66	250	-1.7
2	57	240	-2.0
2	65	240	-5.7
2	65	240	-3.7
2	59	240	-3.6
2	44	270	-6.2
2	41	270	-8.3
2	43	270	-4.2
3	54	0	-11.9
3	30	0	-7.4
3	41	15	-12.4

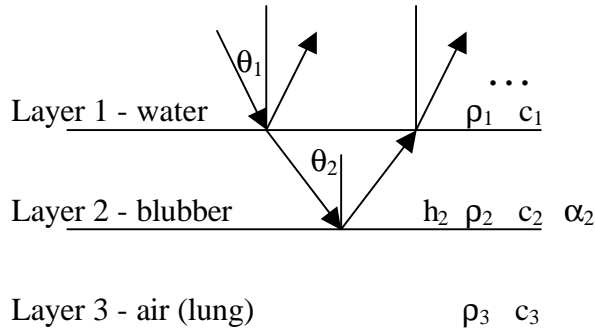


Fig. 4. Three-layer model for plane wave reflection from the lung of the whale.

The reflection coefficient from the water and blubber is R_{12} , the blubber-air reflection coefficient is R_{23} , and the reflection from the structure is R_{13} . R_{13} is given by Medwin and Clay [3] as

$$R_{13} = \frac{R_{12} + R_{23} \exp(-2i\Phi_2)}{1 + R_{12}R_{23} \exp(-2i\Phi_2)} \quad (3.1)$$

where

$$\Phi_2 = k_2 h_2 \cos q_2 - i a_2 h_2 \cos q_2, \quad (3.2)$$

$$R_{12} = \frac{r_2 c_2 \cos q_1 - r_1 c_1 \cos q_2}{r_2 c_2 \cos q_1 + r_1 c_1 \cos q_2}, \quad (3.3)$$

c_1 , ρ_1 are the sound speed and density of the first medium (water), c_2 , ρ_2 , h_2 and α_2 are the sound speed, density, thickness, and attenuation of the second medium (blubber), and c_3 , ρ_3 are the sound speed and density of the third medium (air-lung).

Measurements of the acoustic properties of right whale blubber were made after a right whale was struck and killed by a ship in Cape Cod Bay. A core of blubber was made and measurements were logged on a Geotek Multisensor Core Logger. The core is shown in Fig. 5.

The core consisted of a layer of skin with thickness of 2 cm over a blubber layer with a thickness of 35 cm over a 3 cm layer of muscle. The skin was found to have a compressional sound speed of 1700 m/s and density of 1200 kg/m³. The sound speed for the whale blubber was found to be about 1600 m/s and the density was found to be 900 kg/m³. The attenuation was assumed to be 1 neper/m consistent with measurements of other fatty tissues at 100 kHz.[4] For 20 kHz, we have assumed that the attenuation is 0.2 neper/m. The skin and muscle have been ignored.

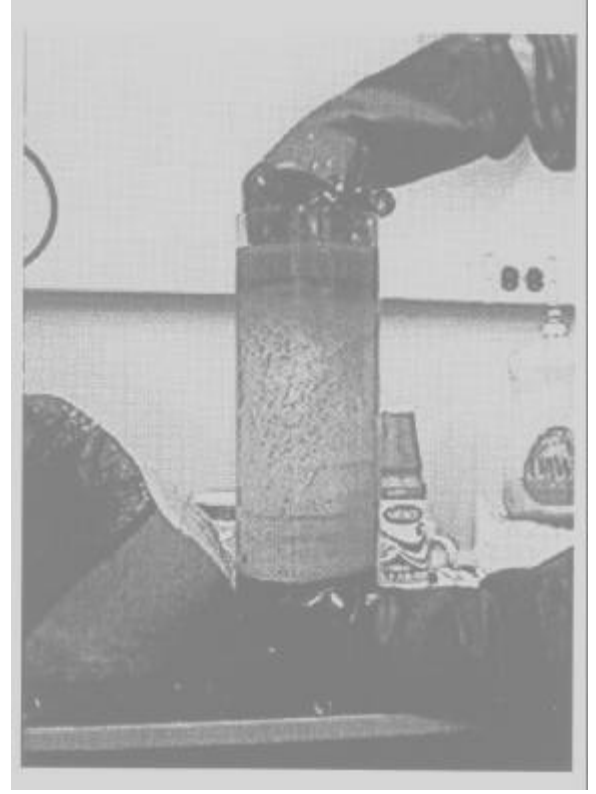


Fig. 5. A sample of right whale blubber being prepared to be logged by the URI Multisensor Core Logger. The blubber was taken from a right whale struck and killed by a ship in Cape Cod Bay.

Figure 6 shows the composite reflection coefficients in dB for the two frequencies of interest: 20 kHz for Love and 86 kHz for our data set. The angle of incidence is assumed to be 0 deg. The difference of 5 dB between right whale and Love humpback measurements seems to be explained by losses in the blubber. The similarity between our humpback measurements and Love's can be explained by the fact that the humpback has a thinner blubber layer and the TS would be more frequency independent.

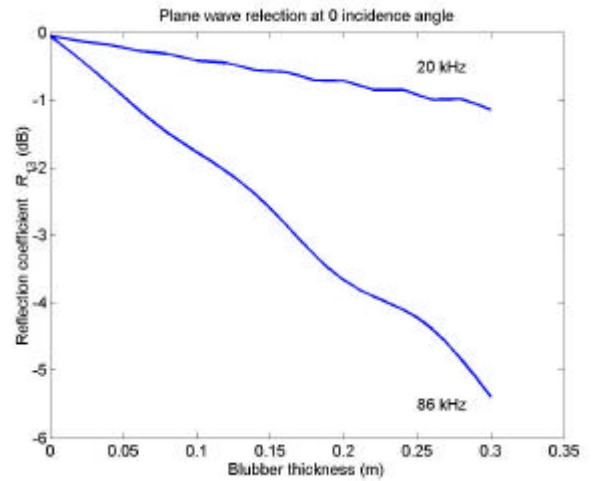


Fig. 6. Plane wave reflection coefficient for the three-layer model of water-blubber-lung for two frequencies: Love's 20 kHz and our 86 kHz.

IV. SUMMARY

Forward-looking sonar has the potential to provide warning of the presence of large whales ahead of shipping. System performance modeling and design for such sonars requires target strength for the whales. This paper has presented measurements made by a forward-looking sonar at 86.25 kHz. Target strengths for humpbacks and northern right whales were collected. These results have been compared to published data by Love and differences have been explained by frequency and blubber thickness of species involved.

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