

Effects of Sound on the Marine Environment

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LONG-TERM GOALS

The long-term goals are to develop novel techniques to predict the effect of sound on the marine environment (ESME). This includes acoustic source modeling, propagation modeling and animal behavior modeling as well as obtaining the appropriate environmental information such as bathymetry, sound speed and seabed properties.

OBJECTIVES

The overall objective of this research is to develop the best possible modeling tools for estimating the impact of sound on marine life. The goal is to provide state-of-the-art, open source codes to model sound sources, sound propagation and animal behavior. We will also assemble open source environmental databases for quantities such as seabed properties, bathymetry and ocean sound speed. Together, these tools will provide the best estimate of the impact of various sonar systems on the marine environment. These tools are bundled with a simple user interface in the ESME Workbench and are intended to be a type of gold standard for estimating impact. Currently, Navy environmental impact statements are prepared at the Naval Undersea Warfare Center (NUWC) and by several government contractors. The software and databases being used are often either classified or proprietary. Starting in 2007, ONR put together a team consisting Boston University (David Mountain), Biomimetica (Dorian Houser) and HLS Research (M. Siderius and M. Porter) to build the ESME Workbench to make the needed calculations for assessing environmental impact without using classified or proprietary components. In 2008 there were two main areas of research at HLS, 1) Quantifying different methods for modeling sonar impact. 2) Determining, through modeling, if strong sound focusing events can occur from surface reflections under specific circumstances (i.e., glints from the surface).

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APPROACH

Approach to quantifying different methods for modeling sonar impact

Currently, environmental impact statements (EIS) are developed in several places both within the government and through contractors. This has led to multiple methodologies being used to analyze, for example, marine mammal take numbers. These various methodologies may eventually lead to confusion and contradictions over the “correct” way to develop an EIS. The Naval Undersea Warfare Center (NUWC, Newport RI) is currently responsible for many of the Navy EIS’s and while NUWC has a number of impact modeling software tools these are generally different from those used by contractors and also those being used in the ESME Workbench. The ESME Workbench software has been under development over the past several years but in FY08 a much closer working relation with NUWC was established to better understand their approaches. In 2008 we also began the process of analyzing differences between a statistical approach to predicting takes as compared to using animal movement models. Currently, NUWC has been instructed (through N45) that animal movement models (i.e. with animats) are a required part of the EIS. The alternative statistical approaches have been used in, for example, the Hawaiian Range Complex (HRC) EIS. It is currently very difficult to reconcile differences between the two methodologies. There may be significant computational advantages to using a statistical approach; however, it is less intuitive and may not treat the temporal component to the problem effectively.

The approach to this comparison starts with understanding the methods and the eventual goal is to quantify differences. However, generalizations of our approach to quantifying differences will also be extremely valuable in providing guidance to users of the ESME Workbench. Since there are often many trade-offs between modeling sophistication and accuracy, the methods developed here can be used to decide if a given approach is warranted.

The three common methods used when trying to analyze sound source impact are 1) using a 2-D animal density, 2) 3-D animal density (including depth) and 3) using simulated animals (animats). Each of these methods is briefly summarized below:

1. 2-D Distribution: This method has been used in the past and assumes a uniform animal distribution in range and bearing and neglects any effects of species dive patterns or temporal motion. As a conservative measure, this assumes that each animal will be exposed to the worst-case sound exposure level in depth. Figure 1 illustrates this and indicates an acoustic field, with maximum sound level taken in depth, and projected onto a 2 dimensional surface.

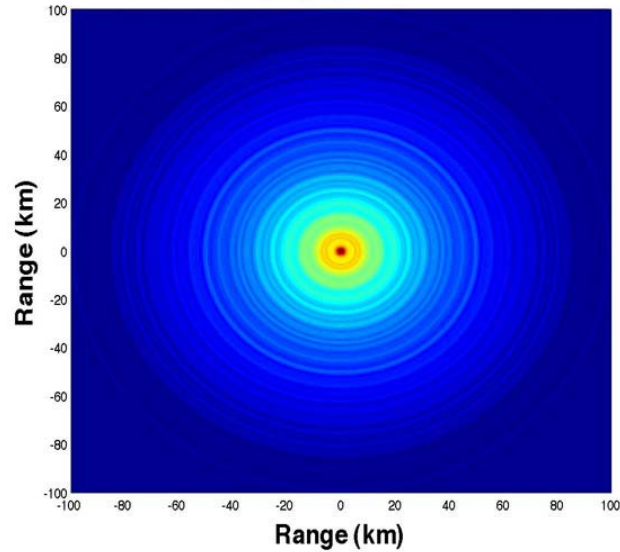


Figure 1: *Omnidirectional source centered at the origin with maximum sound exposure projected onto 2-D surface. For 2-D distribution approach, animals are assumed uniformly distributed over this surface.*

2. 3-D Distribution: This method accounts for a species location in depth by assuming a particular diving behavior for the species. The animal's statistical distribution in depth is generally derived from collected data or using a data driven animal movement model such as Biomemtica's 3MB. An example of a simulated depth distribution profile is shown in Fig. 2.

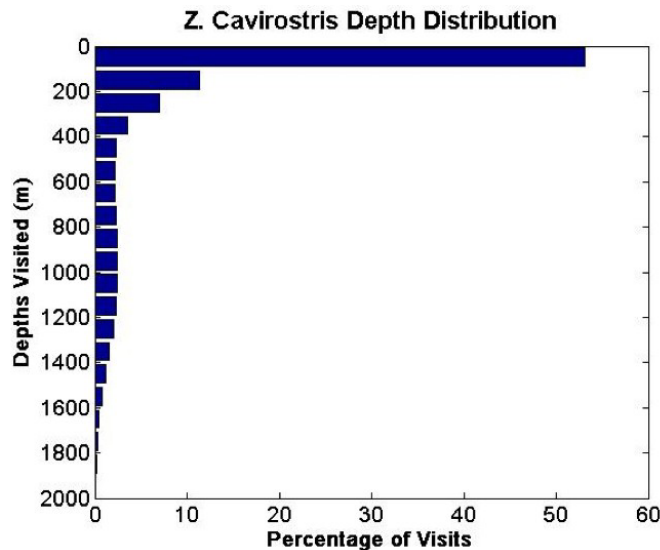


Figure 2: *Example of a depth distribution for a typical diving pattern taken for Z. Cavirostris (deep diver).*

3. Animats: Using Biomemtica's 3MB software, animals (animats) are randomly distributed in an area of interest and their swimming behavior is simulated over time. Using each animat position, with respect to time, we can determine the animat's accumulated sound energy exposure and its maximum

received sound pressure level. Figure 3 shows an ensemble of animats distributed in a box-shaped area and traces of their temporal motion.

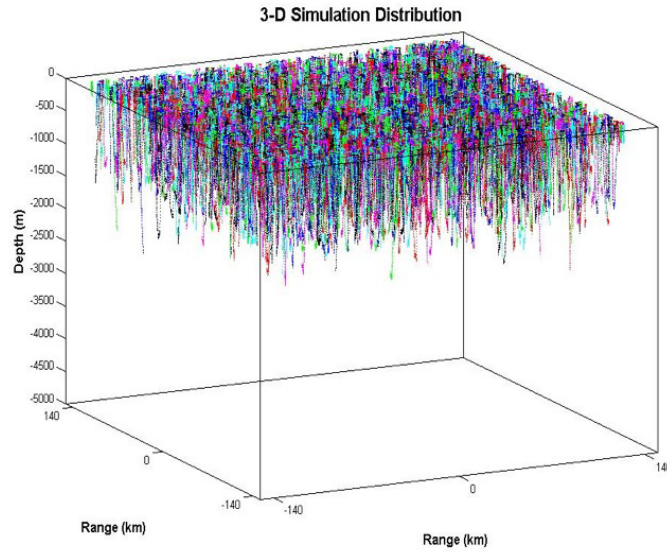


Figure 3: Ensemble of *Z. Cavirostris* simulated using 3MB over a one-hour period. Each line represents the path of an individual animat. Qualitatively, there is a random distribution and differences in individual dive patterns.

All comparisons between items 1-3 above were made based on a generalized, range-independent environment as displayed in Fig. 4. The ray/beam coded Bellhop [1,2] was used as the acoustic propagation model with the environmental parameters scenario dependent but generally this was modeled on the AUTECH range near the Bahamas. An example of a convergence zone sound field and a typical deep water sound speed profile are shown in Fig. 5. Maximum ranges for the simulation were based on a 120 dB minimum threshold to be considered for a take, which is typically 80-140 km for mid-depth and deep-water scenarios.

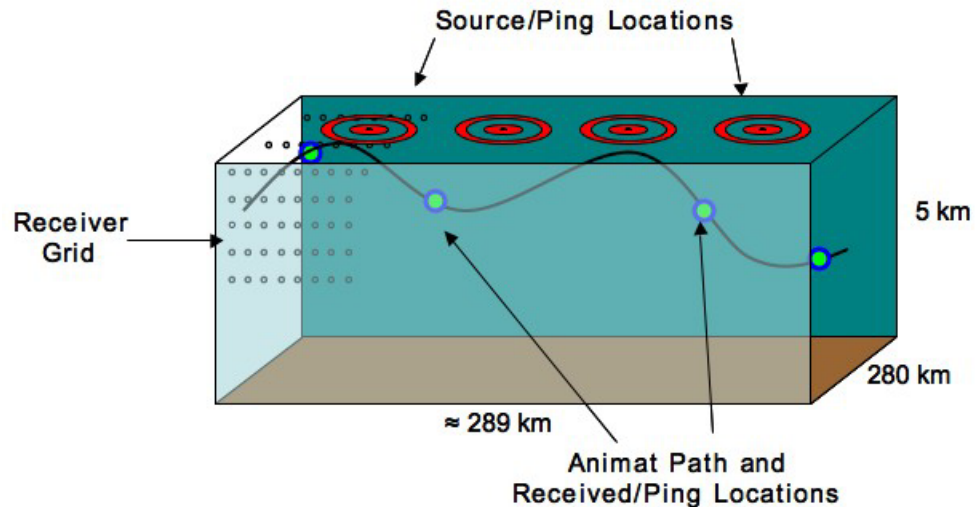


Figure 4: Geometry for the quasi-static simulations. A generalized, range-independent environment with uniform, Cartesian receiver grid was used. Notional animal swim pattern is shown as the thin black line and the source positions as red circles on the surface.

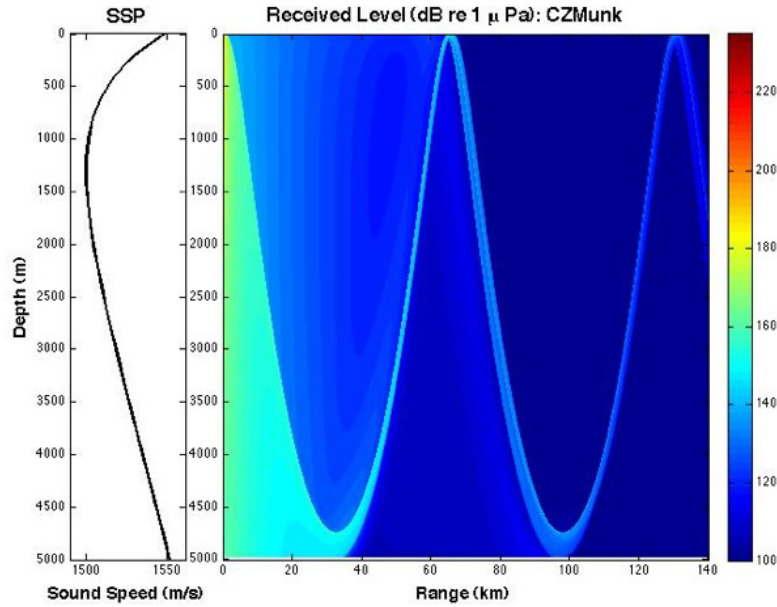


Figure 5: Left panel shows a typical deep water sound speed profile and the right panel the corresponding transmission loss. There are convergence zones in the sound field where focuses occur due to the refracted paths in the water column.

A representative population of 4,050 animals was determined based on the size of the analysis area and an animal density of 50 animals per 1,000 square km. For approaches 1 and 2 (the 2-D and 3-D distributions), the densities were made to be uniform and static in range (across the surface), with a depth distribution used for the 3-D analysis as described. For approach 3 (animats), multiple realizations of 4,050 populations were used to obtain reliable averages and variances. That is, to “average out” the effects of any particular random animal distributions.

The same source parameters were assumed for each simulation. The omni-directional source was placed at the center of the box, with an assumed a speed of 5 knots and ping repetition rate of 30 seconds. The acoustic propagation was modeled using Bellhop with a source level of 215 dB (re 1 μ Pa) and a frequency of 3.0 kHz.

In addition to comparing the three approaches and determining convergence, we also found significant differences in the net effects when mammals with different dive patterns were considered. For this reason, three different mammals were simulated: P. Phocoena (shallow diver), B. Musculus (mid-depth diver) and Z. Cavirostris (deep diver). Results and comparisons between approaches 1, 2 and 3 are shown in the results section for Z. Cavirostris. Additional examples of useful comparisons might include variations of: species, sound speed profiles, bathymetry, source parameters and acoustic modeling methods.

The calculation for takes can be somewhat involved. Level A and Level B (TTS) takes are relatively straightforward to compute since these mostly occur in the near field before complicated propagation effects are involved. However, the Level B behavioral take involve a probability function (a risk function) that gives a chance of a take as far down as 120 dB received sound exposure. For typical

sonar sound sources this can involve propagation ranges of 10's to 100's of km. For the results shown here, both Level A and B (TTS and behavioral) takes are considered.

Approach to modeling surface focusing effects

One of the challenges in acoustic propagation modeling is correctly predicting focusing effects that can produce areas of high intensity sound. This may be critically important to understanding the impact of sound on marine life. This might occur under particular circumstances where the curvature of the sea-surface waves act as type of concave mirror. We have developed a modeling approach for propagation in a waveguide in the presence of surface waves using the virtual source technique, also known as the source superposition technique [3-8]. The virtual source technique has previously been used to compute propagation in a range-dependent, elastic waveguide [9], however, here we apply the method to compute propagation in an oceanic waveguide with a curved surface. The virtual source technique is used to impose boundary conditions on the boundary surface, which is accomplished by placing sources with complex unknown amplitudes near the boundary and requiring boundary conditions to be satisfied on it. This results in a set of equations from which the source amplitudes can be determined. The functions representing the sources must satisfy the wave equation and the radiation condition. In a waveguide, it is convenient to use sources, which satisfy the waveguide boundary conditions. It is, therefore, most common to use the waveguide Green's function to represent the virtual sources. These Green's functions are easily computed using existing propagation models such as Bellhop.

WORK COMPLETED

Work completed on quantifying different methods to modeling sonar impact

We have developed an approach to quantify differences between the various methodologies currently being used for calculating the impact of sonar on marine mammals. This is important since different methodologies raise the obvious questions "do different methods produce the same result and if not, which is correct?" Understanding how various approximations change the outcome allows us to provide the ESME Workbench with the best tools for estimating impact. The ESME Workbench is intended to be a type of gold standard for estimating impact. Generalizations of our approach described here to quantify differences will also be extremely valuable in providing guidance to users of the ESME Workbench. Since there are often many trade-offs between modeling sophistication and accuracy, the methods developed here can be used to decide if a given approach is warranted.

Work completed on modeling surface focusing effects

The theoretical framework for modeling surface focusing effects has been developed as well as preliminary results. Some of the results are presented in the next section, and a journal article is in preparation more fully documenting the approach and results.

RESULTS

Results on quantifying different methods to modeling sonar impact

Many different scenarios and can be contrived by varying the environments, changing source parameters and considering multiple species but some typical cases have been selected for illustrating the results. To best compare the 3-D statistical approach (method 2) with the animat realizations

(method 3), the depth distribution for the 3-D approach was derived from the same animat model, namely 3MB. That is, the 3MB model was run for multiple realizations and histograms of animal positions in depth were created as needed for the 3D statistical approach. The same parameters were then used for 3MB when computing using the animat approach.

The following results are for the *Z. Cavirostris* (deep diver) simulated in a range-independent environment with water depth of 5000 meters. All other sonar and environmental parameters are the same as described above with each of the 3 approaches used to quantify and compare number of takes. Figure 6 illustrates large differences when the dive pattern (depth distribution) is neglected. The 2-D distribution indicates an over estimate by, roughly, a factor 8 over the other two methods. Both the 3-D distribution and animat methods are within 5% of each other after 500 realizations of 50 animats per realization (25,000 total). That is, an “over-population” factor of 6 was needed for 3MB convergence in this simulation. This factor, however, was found to vary when considering different environments and species.

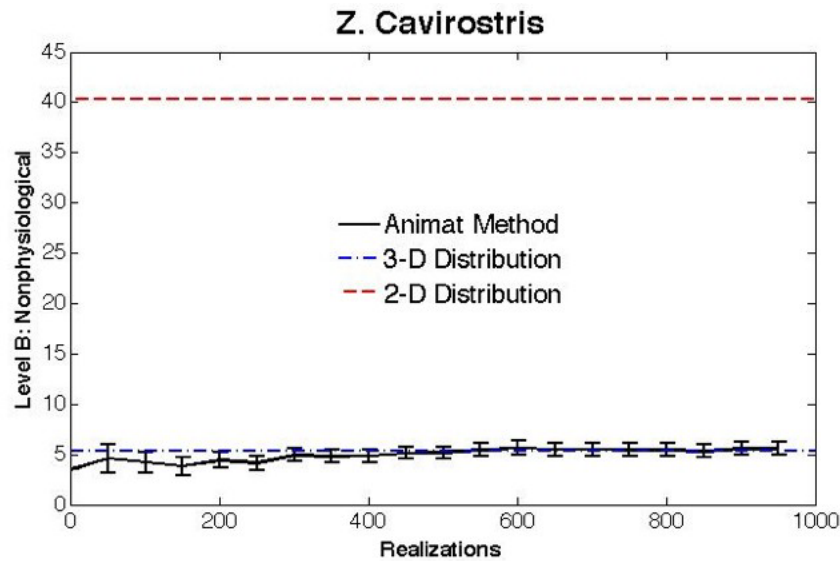


Figure 6: Comparison of methods used for quantifying take values. Neglecting dive patterns results in a gross over estimate. This scenario required 500 3MB realizations (50 animats per realization) for a 5% convergence to a 3-D distribution.

Using 3MB data, we were able to determine exact take locations in depth and range. Figure 7 shows that, for this scenario, the dive pattern and actual take depths are very similar. This result is supportive of a statistical, 3-D distribution approach. Figure 8 is a comparison between the locations of effected animals and the actual number of takes (based on the risk function). Here, we see a correlation between the locations of the number of takes and the animat depth distribution together with peak sound field intensities. Again, this scenario is supportive of a 3-D distribution approach.

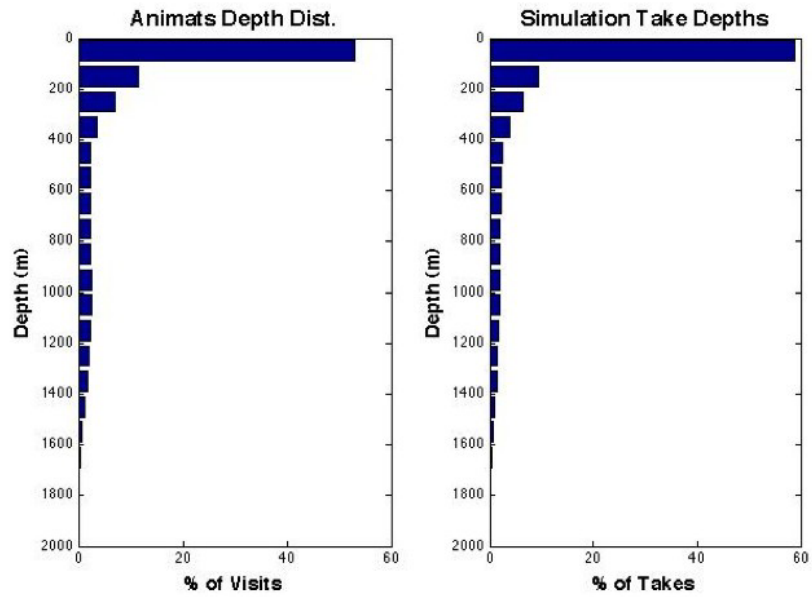


Figure 7: Comparing *Z. Cavirostris* depth distribution (left) with actual take depths (right) using 3MB animats.

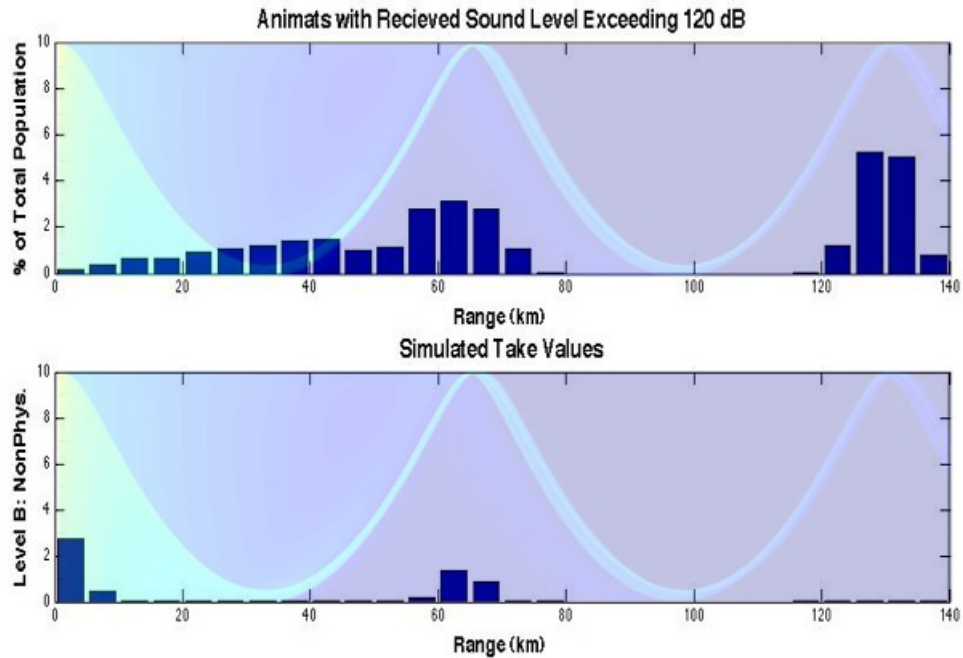


Figure 8: *Z. Cavirostris*: Comparing number of animals affected by min. 120 dB exposure (top) and the associated number of takes determined by the risk function (bottom). The location of the number of takes coincides with animat depth distribution and peak sound field intensities.

Results on modeling surface focusing effects

Preliminary results showing focusing from a curved surface is shown in Fig. 9. In this case a line source 800 m directly below the curvature ensonifies a surface curvature that resembles a slice from a cylinder. This infinite partial cylinder has a height of 2.5 meters and a base of 20 meters. The left panel of Fig. 9 is for 125 Hz and the right for 250 Hz. There is no difference in the intensity of the focus for this case since the curvature and the source are one dimensional.

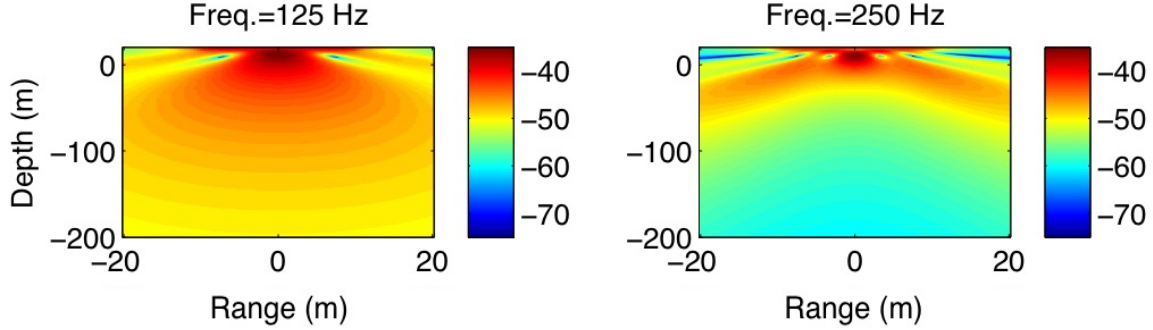


Figure 9: Line source ensonifying a one dimensional curved surface (similar a sliced cylinder). Left panel is for 125 Hz and the right for 250 Hz. In this case doubling the frequency does not increase the intensity of the focus.

For sonar applications it is more realistic to model the source as a point rather than a line, however this is also more difficult. This is possible using the virtual source approach. In Fig. 10 is a similar geometry as presented in Fig. 9 but using a point source. In Fig. 10, the two panels show a 3 dB increase in the focus when doubling the frequency. We found for a point source with a one-dimensional surface curvature, the intensity at the focus is a linear function of frequency.

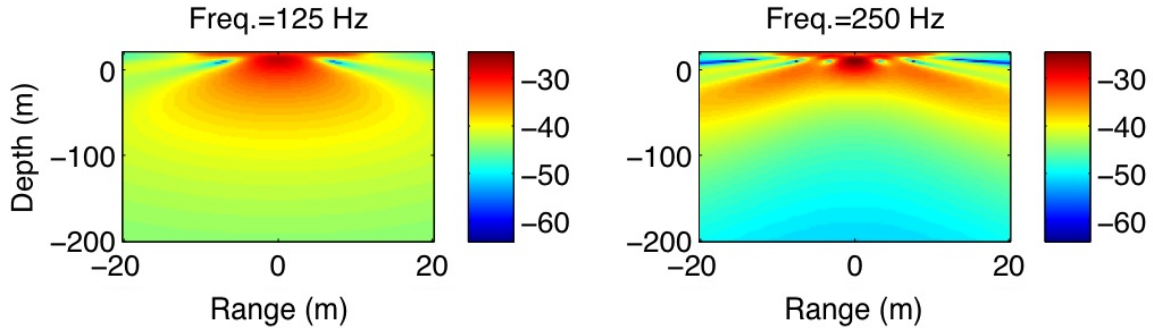


Figure 10: Point source ensonifying a one dimensional curved surface (similar to a sliced cylinder). Left panel is for 125 Hz and the right for 250 Hz. In this case doubling the frequency increases the intensity of the focus by 3 dB.

In Fig. 11, the surface is a segment of a sphere (doubly curved) with a height of 2.5 meters and a base of 20 meters. The left panel shows the intensity when the surface is ensonified by a 125 Hz point source and the right panel shows the same when the source frequency is doubled. It can be seen that when the source frequency is doubled, the intensity at the focus is quadrupled (goes up by ~ 6 dB). We found that when a doubly curved surface is ensonified by a point source, the intensity at its focus is a quadratic function of the frequency.

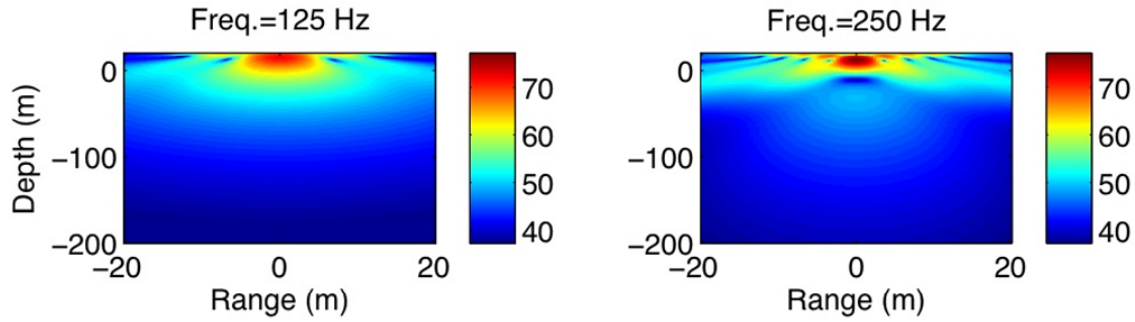


Figure 11: Point source ensonifying a doubly curved surface (similar to sliced sphere). Left panel is for 125 Hz and the right for 250 Hz. In this case doubling the frequency increases the intensity of the focus by 6 dB.

Based on the above results, if the ocean surface during a swell is modeled as a one-dimensional curved surface, the intensity at its focus at higher frequencies can be substantial. It can be even higher if the surface has double curvature. The enhancement in focal intensity for a one-dimensional surface is shown in Fig. 12, where the intensity at the focus due surface curvature for a 4 kHz point source is compared to the case when the surface is flat.

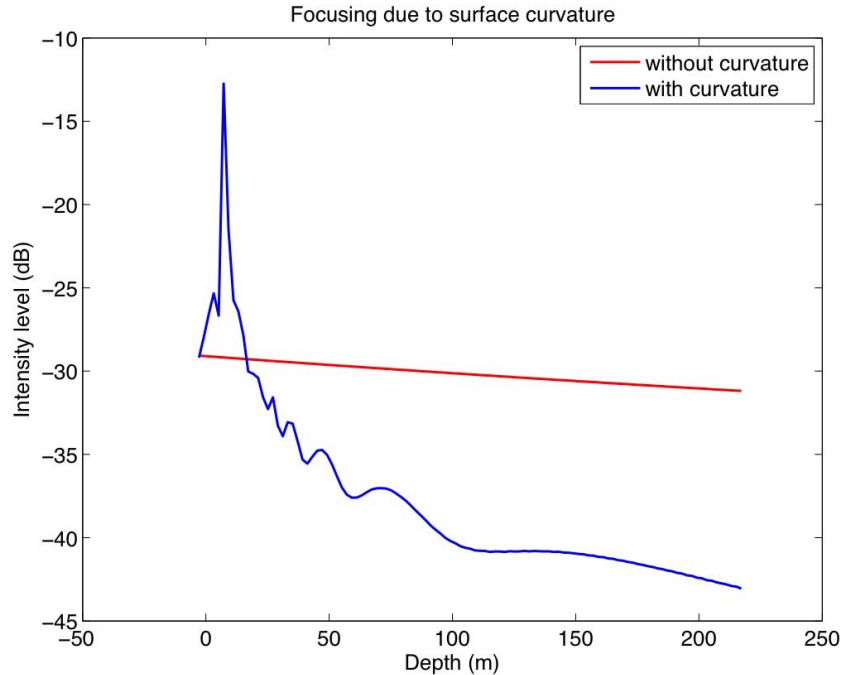


Figure 12: Point source ensonifying a doubly curved surface (similar to sliced sphere) at 4 kHz. The blue line has curvature and the red line is for a flat surface. The peak in the blue line indicates the significant focusing that can occur with a curved surface.

IMPACT/APPLICATIONS

This work is bringing together state-of-the-art acoustic modeling and marine mammal behavior modeling into a simple, intuitive and open source software package. We envision this software will be highly useful for preparing and evaluating environmental assessments to estimate risk to marine life. We also envision the research community will have interest in the developed software to aid in understanding how sound is used both by humans and by marine life in the ocean. The comparisons

between approaches to calculating impact described here is central to providing the best tools and insuring reliable (converged) results.

TRANSITIONS

None at this time.

RELATED PROJECTS

The ESME research on acoustic modeling is being done in close collaboration with ONR Ocean Acoustics projects by Martin Siderius and Michael Porter.

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PUBLICATIONS

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