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WOODS HOLE OCEANOGRAPHIC INSTITUTION

Applied Ocean Physics and Engineering Department

May 14, 2020

Dr. Robert H. Headrick
Office of Naval Research, Code 322
One Liberty Center
875 N. Randolph Street
Arlington, VA 22203-1995

Dear Dr. Headrick:

Enclosed is the Final Report for ONR Grant No. N00014-18-1-2172 entitled "Analysis of Acoustic Influences of Environmental Parameters in Realistic Submarine Canyon Environments: Special Research Award in Ocean Acoustics, Postdoctoral Fellowship for Brendan DeCourcy," Principal Investigator, Dr. Timothy Duda.

Sincerely,

Paula Eissmann
Senior Administrative Asst II

Enclosure

cc: Administrative Grants Officer
Defense Technical Information Center
Naval Research Laboratory
Grant and Contract Services (WHOI)
AOPE Department Office (WHOI)

**Analysis of acoustic influences of environmental parameters
in realistic submarine canyon environments**

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Award number: N00014-18-S-2172

Final Report

PROJECT GOALS

The overall project goal is understanding acoustic propagation in and around submarine canyons, with an emphasis on how the submarine canyon features drive key propagation behavior. Specific goals include explaining how sound field properties are controlled by strongly range-dependent characteristics of the environment including steep bathymetric slopes, sound speed fronts along canyon shelf-breaks, and internal waves. An understanding of the sensitivity of acoustic measurements to variable environmental features was sought, as well as relative influence of range-variable parameters. An additional goal was to use this information to assist in corrections to acoustic measurements to account for known submarine canyon influence.

METHODS USED

Due to the inherent complexity of realistic range dependence in the ocean, there were numerous problems to overcome in pursuit of this project's goals. Spatial and temporal dependence of ocean sound speed, as well as spatial variability in water depth require some amount of abstraction to develop tractable models. Furthermore, there are trade-offs between model realism, computational complexity, and the ability to derive meaningful physics-based interpretations of model output. With these ideas in mind, two different modeling approaches were undertaken during the course of this project.

First, idealized models may not fully capture the inherent physics, but by isolating dominant acoustic features of ocean phenomena the complexity of analysis can be significantly reduced. This approach is aimed at gaining insight into the physical mechanisms that drive observable acoustic behavior in the presence of ocean features such as sound speed fronts. Additionally, it can produce convenient equations to approximate acoustic response to changes in the environment.

Second, a computational modeling approach capable of incorporating complex scattering from bathymetry and water column features was needed. The computational requirements become significantly higher if scattering in all directions is modeled, but the result is that the modeled output can represent more scattering behavior than can the popular parabolic equation (PE) method. With such a numerical model, the outcome desired is a framework suitable to quantify

the influence of bathymetric variability on acoustic mode coupling, and to determine how scattering (interaction with complex seabed, water mass fronts, and waves) influences the direction of acoustic wave propagation.

WORK COMPLETED AND RESULTS

Shelf slope front modeling

In 2018, one paper was submitted, ultimately being published in the September 2019 “Three-dimensional Underwater Acoustics” special issue of the Journal of the Acoustical Society of America (JASA). This paper, titled “Effects of front width on acoustic ducting by a continuous curved front over a sloping bottom” (DeCourcy et al., JASA, 2019) outlines a model of a curved and continuously varying sound speed front over a sloped bottom. The model is used to assess the features of a continuous sound speed front that are lost in a single interface front depiction, with the goal of identifying when it becomes acceptable to use the simple but convenient single interface model to predict acoustic propagation behavior that is influenced by such a curved front.

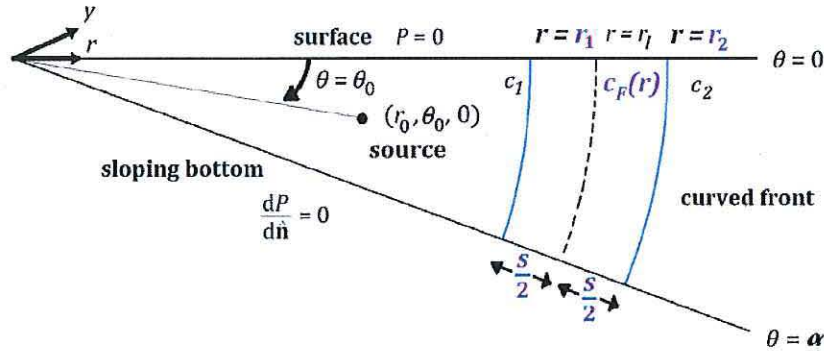


Figure 1: Model geometry for the shelf-slope wedge with continuous sound speed front. Model parameters are: front location at r_1 , front width s , bottom slope angle α , source frequency f , inshore/offshore sound speeds c_1 and c_2 .

Introducing a $1/c^2(r)$ linear sound speed profile along the radial direction shown in Fig. 1, mode functions in a radial normal mode solution for the acoustic pressure took the form of Hankel functions with imaginary order. Asymptotic approximation of the mode shapes for large order and large argument allowed for a numerical solution to the modal wavenumber dispersion relation and analysis of the influence of front width on the acoustic propagation. The most interesting outcome of the continuous front model was the identification of modes that were near resonance in the front. These modes satisfied the approximate equation

$$s\kappa_r \approx N\pi,$$

where the front width is given by s , the average radial wavenumber in the front is given by κ_r , and N is an integer. Radial modes which satisfied this condition that the front width was nearly equal to an integer multiple of $\lambda_r/2$, or half the modal wavelength are considered near resonant.

These modes were of interest, as they possessed a much larger imaginary component to the along-front modal wavenumber, resulting in stronger transmission of acoustic energy through the front. Also evident was that as the front width increased, transmission across the front became stronger, as the frontal refraction weakened.

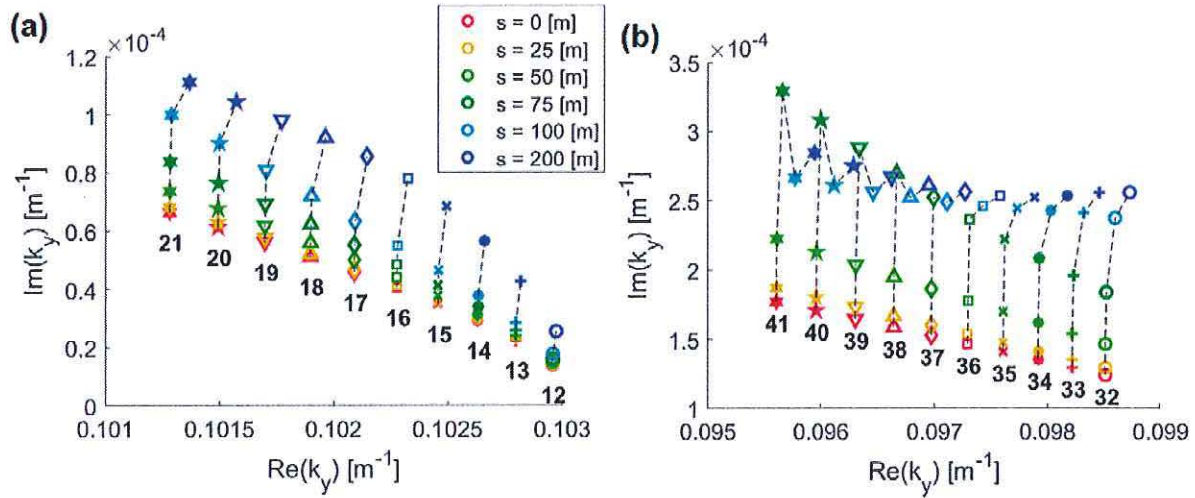


Figure 2: Evolution of eigenvalues in the k_y plane as front width changes. A single radial mode number m is represented by identical symbols connected by dashed lines. A collection of radial modes for a single front width s share the same color. For lower leaky mode numbers (a) it is observed that the imaginary component of along-front wavenumber increases as the front width increases, indicating higher transmission across the front. For higher mode numbers (b) this observation is no longer true, as modes are observed to have a strong imaginary k_y response to some front widths which are associated with near-resonance.

Despite the fact that near-resonant modes and the weaker refraction do not occur in a single interface front model, it was determined that when the interest was in far-field effects of the front on acoustic propagation, the single interface front was capable of capturing the details of along-front propagation.

Omnidirectional acoustic propagation modeling

An important part of the work in this project was creating a framework for studying acoustic propagation in a 3-D environment that exhibited complicated reflection and refraction. To do this, a 3-D coupled mode numerical model was implemented. Previous work on this type of coupled mode modeling (Rutherford et al., 1981), (Fawcett, 1992) was limited to 2-D idealized environments and trapped modes, but a 3-D implementation designed to work for strongly variable bathymetry and include portions of the leaky mode spectrum using bottom attenuation gradients as in Westwood et al. (1999) was developed for this project. This model is detailed in the paper “A coupled mode model for omnidirectional three-dimensional underwater sound

propagation,” which was submitted in late 2019 and is currently under review for publication in JASA. The modeling is intended for environments with strongly variable water depths, such that it can handle typical submarine canyon bathymetry.

An early version of the modeling efforts was presented at the 176th meeting of the Acoustical Society of America (ASA) in Victoria, BC, Canada in 2018. Results from an improved version of the model were presented at the 178th meeting of the ASA in San Diego, CA in 2019. These presentations outlined the numerical techniques used to compute and validate the model, including a 2-D finite element solution method for the 2-D coupled Helmholtz equation that describes the mode amplitudes. The mode coupling present in the Helmholtz equation was analyzed to show the importance of source location in determining the strength of coupling. Mode amplitudes are functions of a mode coupling term denoted as $S_{C,m}$ for mode m , which contains propagation information for all other modes. This coupling term is strongest over regions of steeper bottom slopes, and when the sloped areas are closer to the acoustic source. A plot of the scaled $\log_{10}|k_m^{-1}S_{C,m}|$ for horizontal modal wavenumber k_m is shown in Fig. 3, which illustrates this point for a 50 Hz sound source around the Hudson Canyon.

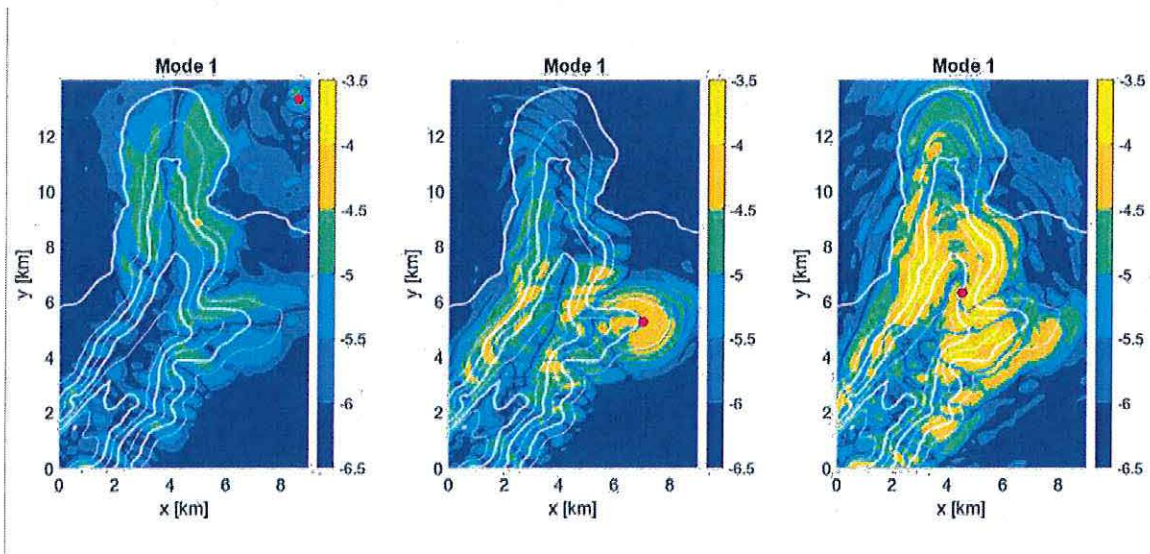


Figure 3: Coupled source term. White lines represent constant bathymetry levels at 100 m spacing (thick) and 50 m spacing (thin). The source is denoted by a pink circle. Yellow regions indicate stronger coupling. The strength of the coupling is observed to rely on source proximity to sloped bathymetry, as well as the steepness of the slope.

Another point illustrated in these presentations and in the submitted paper is the difference between a coupled and adiabatic model of sound propagation. It is well understood that adiabatic approximations are not viable for strongly range-dependent environments, but due to the relative simplicity of the adiabatic approach, it was of interest to understand what qualities of canyon propagation it could handle.

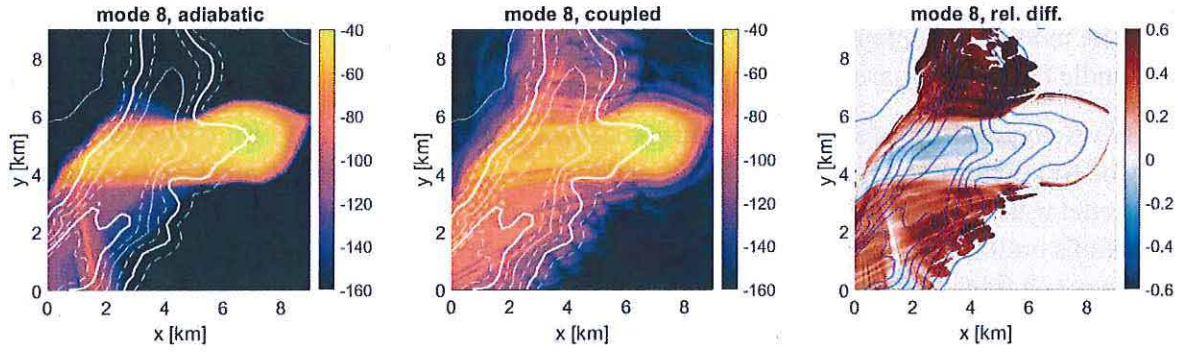


Figure 4: Mode amplitudes for 8th vertical mode from a 50 Hz source in Hudson Canyon. Adiabatic mode amplitude illustrates refraction from the decreasing water depth due to the canyon walls, while coupled mode amplitude shows energy carrying by higher modes into shallower water.

Comparisons of adiabatic and coupled mode amplitudes revealed that while adiabatic approximations could capture some of the canyon refraction properties, higher modes especially were carried by coupling into canyon regions that adiabatic assumptions ruled out. Figure 4 illustrates this behavior for vertical mode 8 due to a 50 Hz sound source in the Hudson Canyon. The relative difference in the modal amplitudes is given as

$$diff = 2 \frac{\log_{10}|R_C| - \log_{10}|R_A|}{|\log_{10}|R_C| + \log_{10}|R_A||}$$

in Fig. 4. This testing concluded that modes that possess strong horizontal attenuation near the sound source may still propagate longer distances than otherwise expected due to energy exchange with slowly attenuating modes that is represented in the mode coupling.

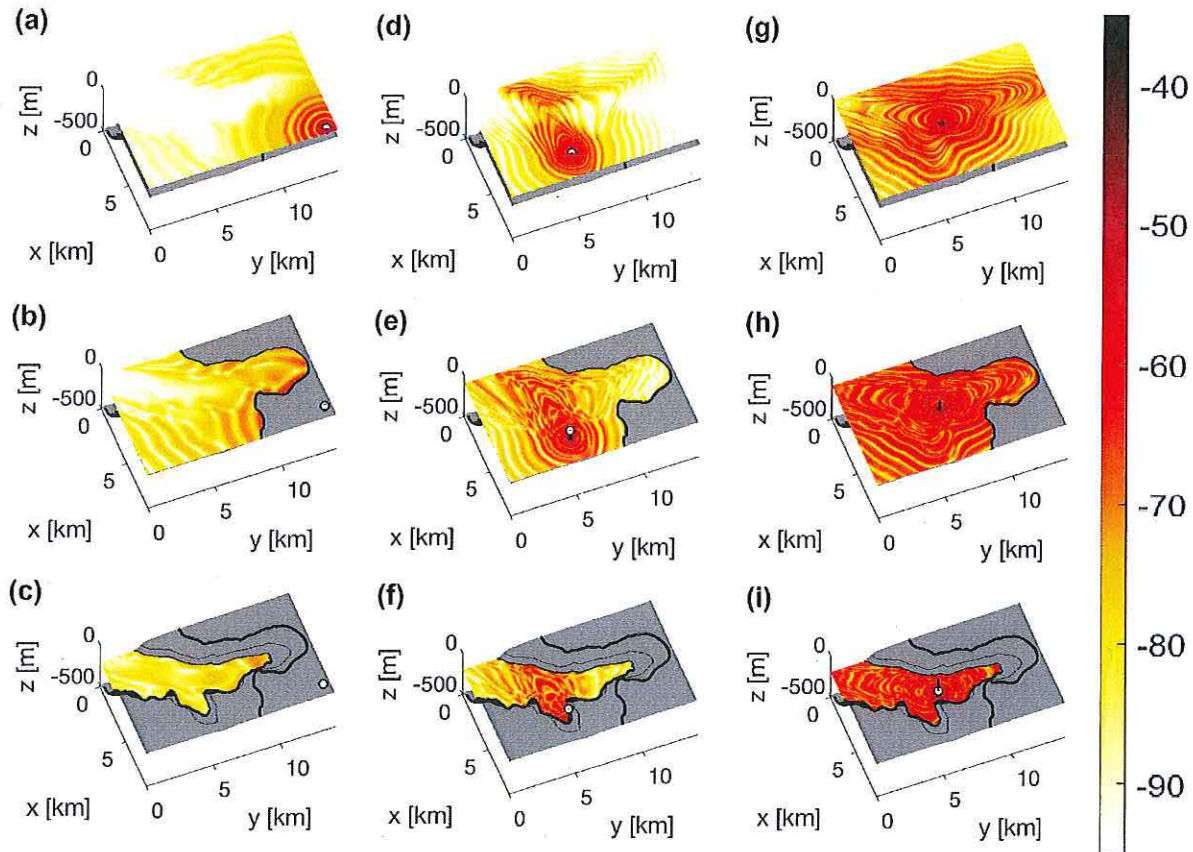


Figure 5: Horizontal cross sections of transmission loss at 8, 100, and 200 meters for three source placements. (a)-(c), S1 at 8 m depth, (d)-(f) S2 at 8 m depth, (g)-(i) S3 at 150 m depth.

Estimating direction of arrival (DOA) bias due to canyon bathymetry

A final paper is currently in progress, which discusses the influence of the canyon bathymetry on estimated DOA calculations. By inserting virtual receiver arrays in the computational domain, estimates for the direction of strongest arrival are computed, and can be compared to true direction to the source to arrive at a bias estimate. These biases are observed to be influenced both by the location of the sound source and the canyon bathymetry. Figure 6 illustrates the outcome of a conventional beamforming approach for estimating the horizontal direction of arrival, with bias measured in degrees offset from the true direction to the source.

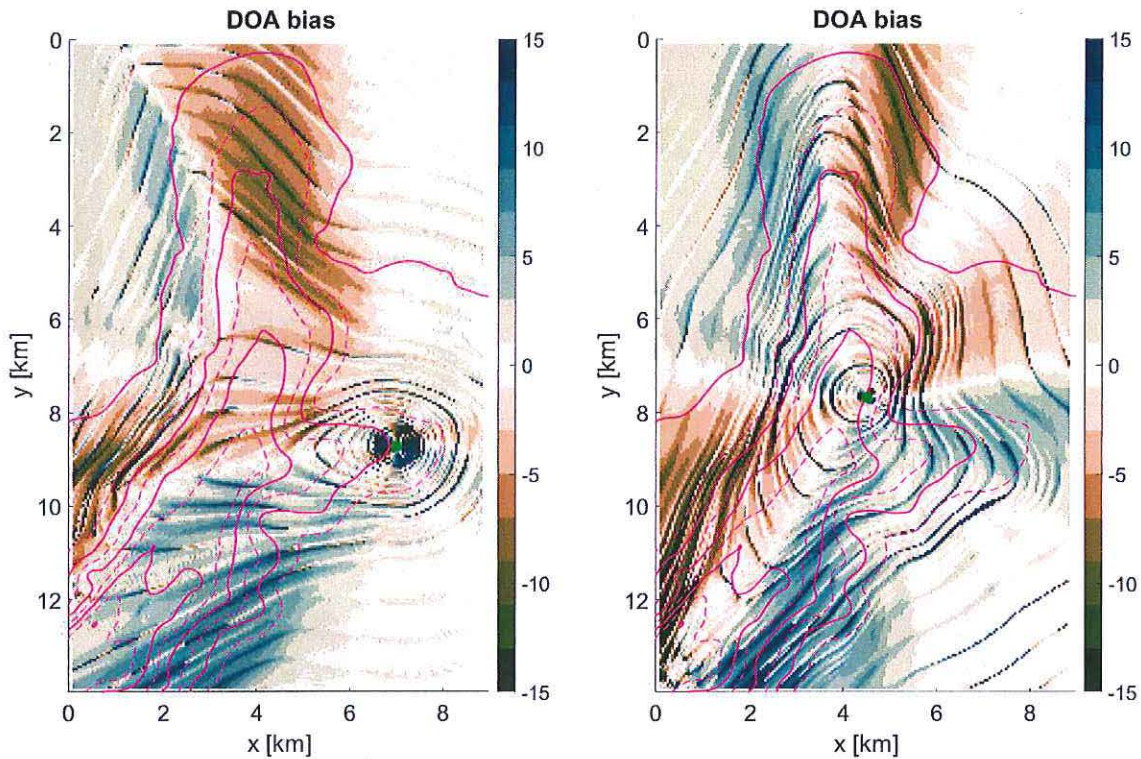


Figure 6: Horizontal direction of arrival bias in the Hudson Canyon for a 50 Hz sound source at two separate locations. Green areas experience a clockwise bias in reported DOA, while orange areas experience a counter-clockwise bias. Bias is reported in degrees.

REFERENCES

- B. J. DeCourcy, Y.-T. Lin, W. L. Siegmann, "Effects of front width on acoustic ducting by a continuous curved front over a sloping bottom," *J. Acoust. Soc. Am.* **146**, 1923 (2019).
- S. R. Rutherford, K. E. Hawker, "Consistent coupled mode theory of sound propagation for a class of nonseparable problems," *J. Acoust. Soc. Am.* **70**, 554 (1981).
- J. A. Fawcett, "A derivation of the differential equations of coupled-mode propagation," *J. Acoust. Soc. Am.* **92**, 290 (1992).
- E. K. Westwood, R. A. Koch, "Elimination of branch cuts from the normal-mode solution using gradient half spaces," *J. Acoust. Soc. Am.* **106**, 2513 (1999).

RESULTS DISSEMINATION

B. J. DeCourcy, Y.-T. Lin, W. L. Siegmann, "Effects of front width on acoustic ducting by a continuous curved front over a sloping bottom," *J. Acoust. Soc. Am.* **146**, 1923 (2019).

B. J. DeCourcy, T. F. Duda, "A coupled mode model for omnidirectional three-dimensional underwater sound propagation," *J. Acoust. Soc. Am.* (Under review)

The P.I. also co-wrote a paper that was published as:

M. A. Milone, B. J. DeCourcy, Y.-T. Lin, and W. L. Siegmann, "Parameter dependence of acoustic mode quantities in an idealized model for shallow-water nonlinear internal wave ducts," *J. Acoust. Soc. Am.* **146**, 1934 (2019).

CONFERENCE PRESENTATIONS

The PI attended and presented at the 176th Meeting of the Acoustical Society of America, Victoria, BC, Canada in November 2018. B. J. DeCourcy, T. F. Duda "Perturbation approximations for bathymetrically controlled ocean acoustic mode coupling."

The PI attended and presented at the 178th Meeting of the Acoustical Society of America, San Diego, California, in December 2019. B. J. DeCourcy, T. F. Duda, "Mode coupling and scattering in a submarine canyon environment."

