Analysis of 3-D Propagation Effects Due to Environmental Variability

Kevin B. Smith
Code PH/Sk, Department of Physics
Naval Postgraduate School
Monterey, CA 93943
phone: (831) 656-2107 fax: (831) 656-2084 email: kbsmith@nps.edu

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LONG-TERM GOALS

The goals of this work were multi-faceted, consistent with the various efforts supported by this work. Particular focus was placed on predictions and analysis of the three-dimensional (3-D) propagation in the presence of 3-D environmental variations, especially shelf break canyons. Work was also performed in support of 2-D propagation in shallow water to study the impact of bottom roughness and water column variability on arrival structure coherence. Additional modeling efforts were undertaken to examine the accuracy of the treatment of the bottom density discontinuity. By continuing to expand and improve the capabilities of the numerical modeling methods, the long-term goal of this effort is to provide a useful tool for understanding the physical phenomena leading to variability in shallow water acoustic propagation.

OBJECTIVES

The overall objective of this work was to study the response of the acoustic field in the presence of environmental variability, and to examine the effects of 3-D topography on shallow water propagation.

APPROACH

This work continued and expanded upon previous efforts to study the effects of environmental variability on the 3-D structure of the total acoustic field (pressure, particle velocity, acoustic intensity, etc). In FY12, the formal equations for computing 3-D scattering from 2-D rough surfaces were developed. Implementation of these expressions and model validation was the focus of much of the FY13 work. Final model evaluation for various 2-D rough surfaces was completed in FY14. In addition, the typical approach used to model the density discontinuity at the seafloor was revisited. Higher order approximations and hybrid approaches between split-step Fourier and finite-difference schemes were considered.

Also in FY14, a 3-D model written in Cartesian coordinates capable of computing the effects of 3-D bathymetric features was employed to investigate the potential azimuthal coupling occurring during propagation in the Monterey Bay Canyon. This was motivated by observations of highly variable directional features in measured acoustic vector data. Sound speed profiles and bathymetry data for

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the Monterey Bay Canyon were used as inputs to the model, and broadband calculations were performed which allowed for post-processing of acoustic arrival time structure in 3-D.

In addition, a 2-D version of the model previously developed was employed for broadband calculations in shallow water with simple bottom roughness and water column variability in order to study the impact on arrival structure coherence.

Finally, various versions of the 2-D model employing different approaches for treating the bottom density discontinuity were investigated. This included different interface smoothing functions, as well as hybrid methods utilizing both split-step Fourier and finite-difference techniques. Convergence tests were performed in order to determine both accuracy and efficiency of the various approaches.

WORK COMPLETED

In FY12, the analytical expressions for modeling a 2-dimensional rough ocean surface with a 3-dimensional version of MMPE were developed in both cylindrical and Cartesian coordinates. In FY13, a new implementation approach was developed that involved a hybrid method utilizing the split-step Fourier algorithm for range and depth, and a finite-difference algorithm for azimuth/cross-range. In FY14, solutions were computed in cylindrical coordinates for a variety of 2-D rough surface interfaces.

In addition, calculations of 3-D acoustic propagation over rough bottom bathymetry were made in two directions over a region of the Monterey Bay Canyon. The directions coincided with data collected of humpback whale vocalizations that displayed directional bearing ambiguity in the acoustic intensity vector. These calculations were performed broadband in order to compute arrival structure that highlighted horizontal coupling.

Support was also provided to Jennifer Wylie on her PhD dissertation at the University of Miami (under the guidance of Prof. Harry DeFerrari). In this work, 2-D scattering in shallow water due to rough bottom boundaries and internal wave-like features in the water column was investigated. Solutions computed from the MMPE model were analyzed in terms of modal arrival sructures and temporal coherence was used as a measure of the impact of scattering.

In addition, the treatment of the bottom density discontinuity in split-step Fourier models was investigated using various alternative approaches. A thorough set of convergence tests were performed in order to determine which methods produced optimal results, and to highlight issues with certain approximations.

RESULTS

3-D Rough Surface Scattering Studies:
In FY14, various rough surface realizations were investigated to test the response of the new 3-D scattering algorithm. One realization was defined by a smooth, but constant non-zero slope, surface over a flat bottom, which should produce results consistent with a rotated coordinate system consisting of a flat surface and sloping bottom. Other realizations employed sinusoidal fluctuations in the sea

surface height, including a cylindrically symmetric perturbation of repeating sinusoids, a continuous plane surface wave, and discrete single planar sinusoidal perturbations near the source.

Figure 1 represents the results from the initial test, a constant slope (smooth) surface. The left panel displays the TL field along a single radial from the source. (The opposite radial would show a similar field with the surface rising as a function of range.) The right panel displays a similar TL field along a single radial from the source in an equivalent rotated environment with the surface flat and bottom sloping upward. Figure 2 then displays TL traces at 30m above the bottom from both solutions. The agreement indicates that the model is correctly predicting consistent results from the equivalent environments.

Figure 3 provides results from a single, planar (cross-range) sinusoidal depression in the surface. The left panel displays the TL field along a single radial in the direction of the surface displacement. (The opposite radial shows a range-independent surface.) The right panel displays a depth slice in the TL field at 30 m depth (the source depth), which shows the impact of the surface displacement on the right side of the graph, with little effect on the left side. This is also consistent with expectations.

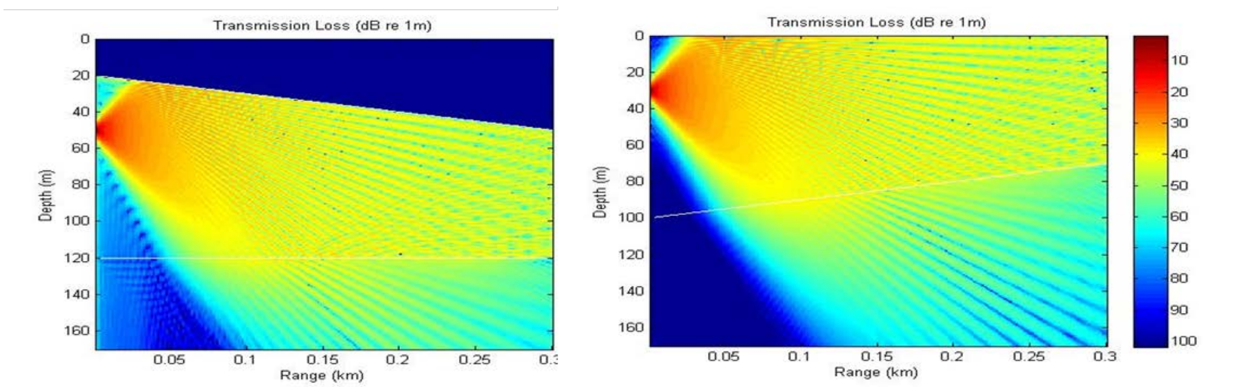

Figure 1: 3-D MMPE test case results for a constant slope, 2-D surface in cylindrical coordinates: TL field along a single radial in the direction of the surface down-slope (left panel); TL field along a single radial in a rotated environment with flat surface and bottom up-slope (right panel).

3-D Scattering from the Monterey Bay Canyon:
In FY13, various whale vocalizations were recorded on a directional sensor in Monterey Bay that displayed significant bearing ambiguity. The bathymetry in the region of the recordings is displayed in Fig. 4 (left panel). The cause of this ambiguity was unclear, which motivated a study of the 3-D scattering in the region of the canyon in FY14. The 3-D MMPE model with variable bottom bathymetry was employed in a broadband mode to allow for arrival time structure calculations. The bathymetry input to the model was extracted from the southwest direction of the recording, as displayed in Fig. 4 (right panel). The model was run for 512 frequencies over a bandwidth of 127.5Hz centered at 400Hz out to a maximum range of 5km. This resulted in a frequency bin size of 0.5Hz, giving a total time window of 4sec. The source depth of the calculation was 92m, consistent with the depth of the recorder at the time of the whale vocalizations being examined.

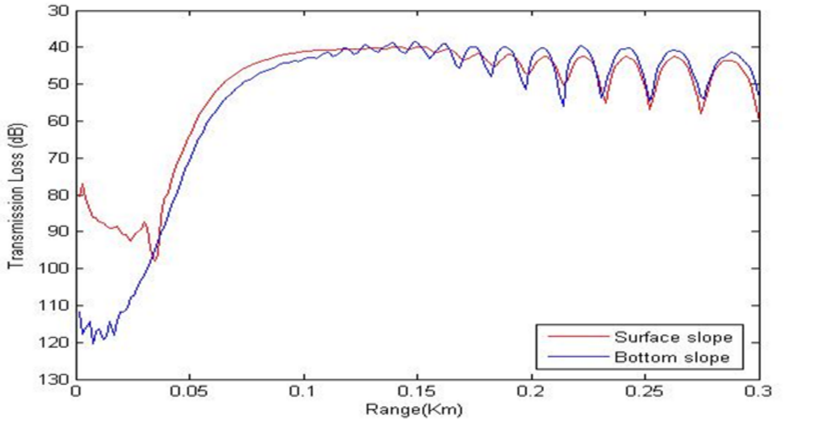

Figure 2: 3-D MMPE test case results for a constant slope surface over a flat bottom compared with an equivalent rotated environment with a flat surface over a sloping bottom. Both calculations were performed in cylindrical coordinates.

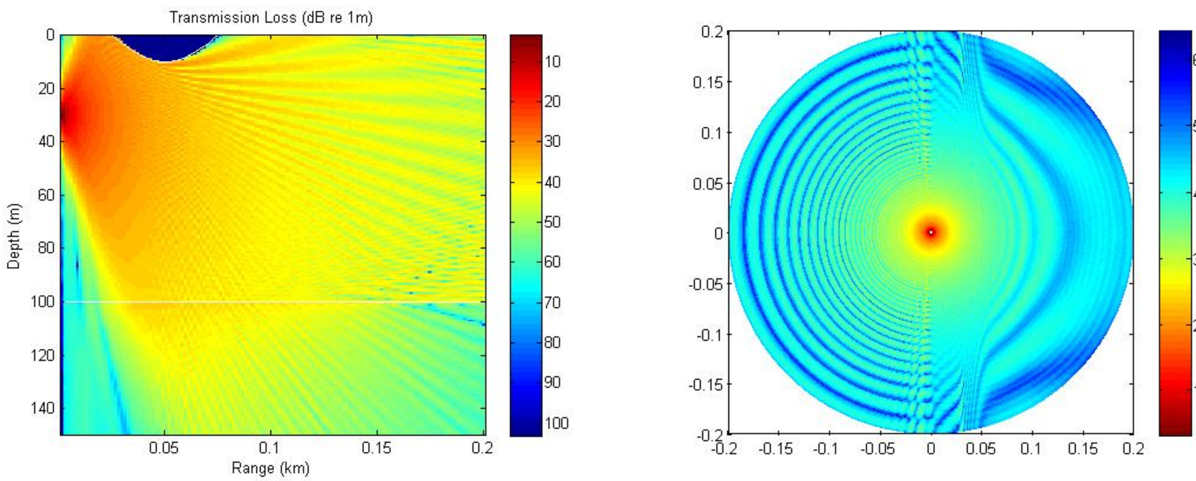

Figure 3: 3-D MMPE test case results for a single, planar, sinusoidal surface displacement in cylindrical coordinates: TL field along a single radial in the direction of the surface displacement (left panel); TL field at a constant depth of 30 m (right panel).

Figure 5 displays arrival time results at the maximum computational range of 5km and at a depth of 50m. The left panel shows the basic arrival time structure as a function of cross-range from the central range axis. Multiple bottom scattering responses can be observed at varying times and appear from different directions, due to the nature of the cross-range bathymetry along the propagation paths. The right panel displays the results of a plane-wave beamformer applied to the travel time data extracted over a 400m aperture centered at -1km cross-range. These results clearly display horizontal scattering due to the bathymetry, exhibiting azimuthal coupling by as much as 40+ deg out-of-plane.

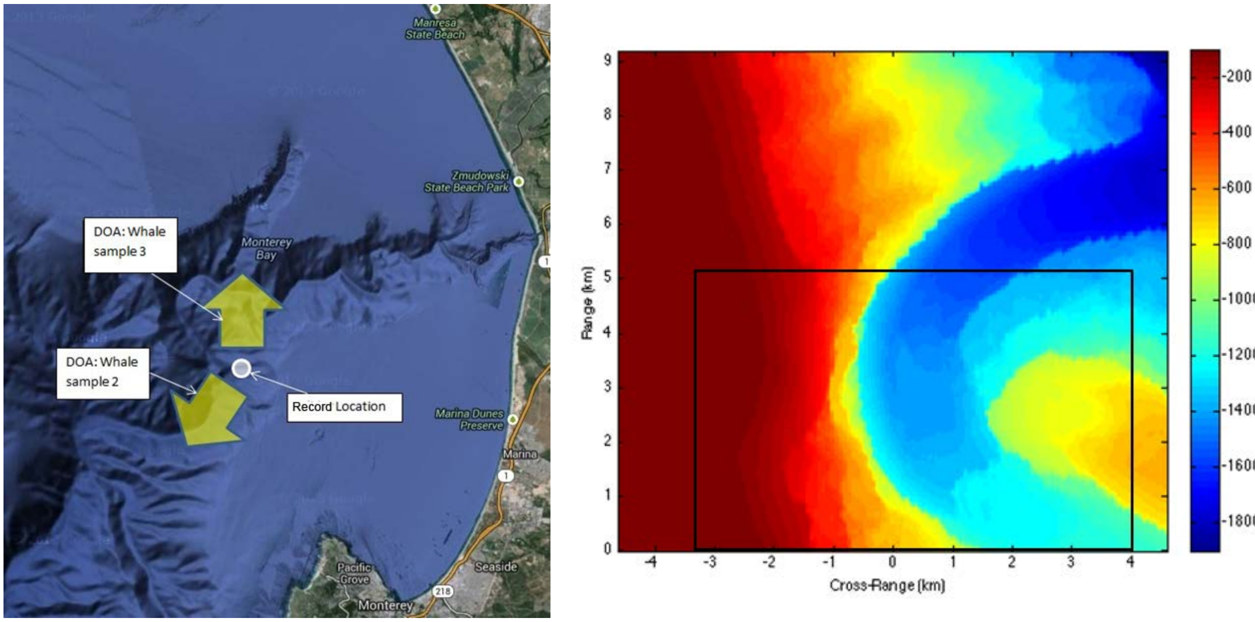

Figure 4: Bathymetry of the Monterey Bay Canyon in the vicinity of whale vocalization recordings (left panel); Monterey Bay Canyon bathymetry data extracted towards the southwest of the recording location for input into 3-D MMPE model (right panel).

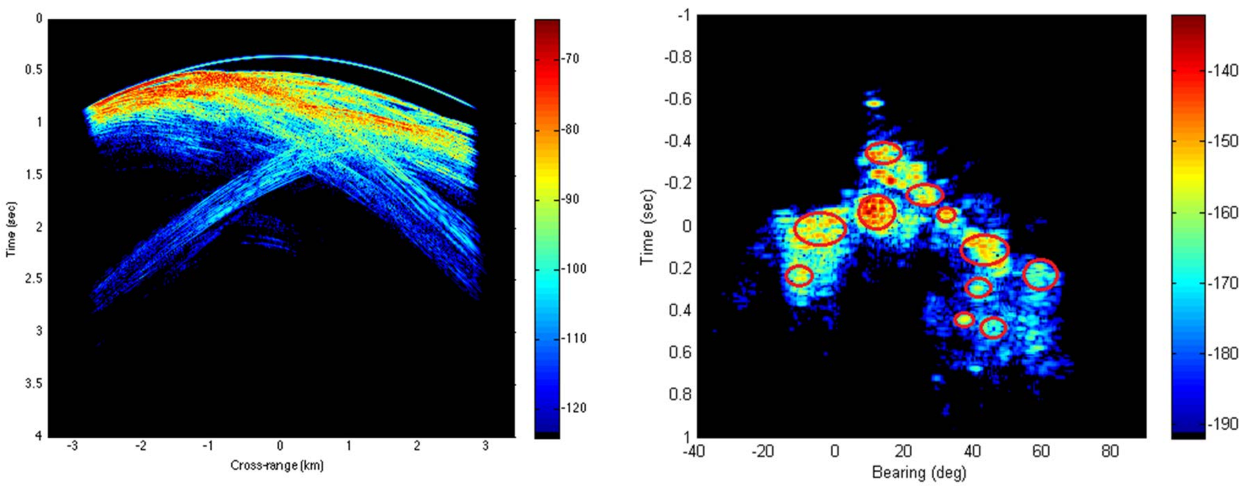

Figure 5: 3-D MMPE arrival time results at 5km range from source over a band of 340-460Hz at a depth of 50m (left panel), and plane-wave beamformed response from this data over a 400m aperture centered at -1km cross-range (right panel, circles highlight dominant bottom scattered arrivals).

2-D Scattering and Modal Coherence in Shallow Water:
Support was provided to Jennifer Wylie at the University of Miami, who utilized a 2-D broadband version of MMPE in her PhD dissertation to study the impact of simple bottom roughness and water column variability on arrival structure coherence. In her work, she computed both spatial and temporal coherence of the PE arrival time structure and used that to infer the impact on modal coherence in shallow water. Her calculations, referred to as PE Mode Arrival Coherence (PEMAC),

showed that higher order modes were more strongly affected by bottom interface variability, whereas the lower order modes were more strongly influenced by water column variability. Further, she showed that the water column variability tends to dominate the loss of coherence at low frequencies (<100Hz), but small bottom fluctuations tend the dominate at high frequencies (>1kHz). Between these frequencies, both water column and bathymetric variability can have a noticeable impact on coherence.

Bottom Density Discontinuity Treatment:
In FY13, the approach historically used in split-step Fourier (SSF) algorithms to treat the density discontinuity at the water/bottom interface was found to introduce small phase errors that accumulated over long range. In FY14, a collaboration with Dave Thomson (Canada) investigated this effect. We assessed various techniques previously defined, including various smoothing approaches as well as extensions of the hybrid split-step Fourier/finite-difference (SSF/FD) algorithm previously described by Yevick and Thomson (1997).

Results of various SSF and SSF/FD model implementations were investigated in a simple Pekeris waveguide of depth 300m out to a maximum range of 20km. Solutions were compared with the Couple97 normal mode model. It was found that proper sampling and parameter specification improved the results of all models. Figure 6 displays results of TL traces at a depth of 100m for a 100Hz source transmitting at a depth of 180m for the normal mode model and various implementation of SSF or SSF/FD PE. In all cases, the agreement with the normal mode solution is good. Future work will continue to examine this issue in order to reduce the free parameter specifications needed to generate accurate results.

IMPACT/APPLICATIONS

The impact of the work done on extending the surface scattering model to 3-D is to allow researchers in future models to directly compute the 3-D, out-of-plane scattering effects of the sea surface. This could also be applied to the development of acoustic communication algorithms, or possibly be utilized to study the effects on high-frequency sonar systems.

The impact of the work done to model 3-D horizontal scattering from underwater canyons is significant, in that it shows the large out-of-plane scattering that can occur in such regions of the ocean near shelf breaks. Future experiments and/or systems that attempt to take advantage of potential focusing effects due to canyons must be prepared to deal with significant bearing uncertainty in arrivals. Such ambiguity may be difficult to predict with any certainty due to the complex nature of the scattering from such bathymetry features.

The studies of the density discontinuity treatment will define improvements to certain propagation models that utilize the split-step Fourier marching algorithm. This will also improve recent models that compute the propagation across all air/water/sediment interfaces, such as recently done to investigate the impact of off-shore, noise-generating platforms on ambient noise both above and below the sea surface. It may also be used to compare with surface scattering models based on field transformation techniques.

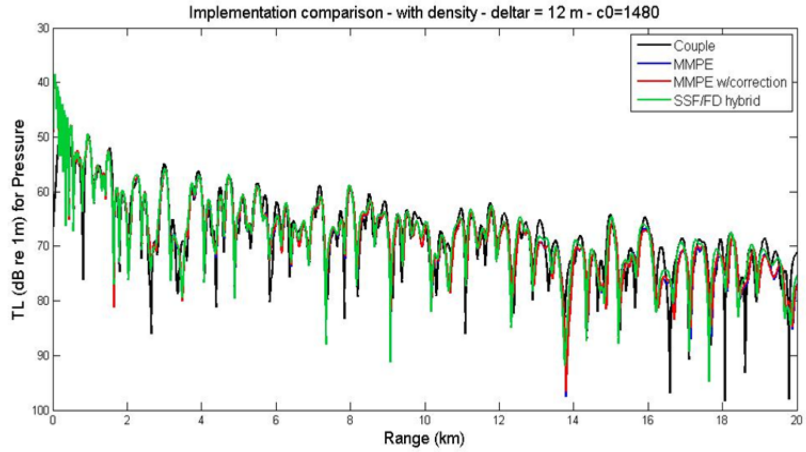

Figure 6: 3-D MMPE test case results for a single, planar, sinusoidal surface displacement in cylindrical coordinates: TL field along a single radial in the direction of the surface displacement (upper panel); TL field at a constant depth of 30 m (lower panel).

RELATED PROJECTS

The work done with MMPE to model 3-D propagation and scattering effects in both the acoustic pressure and velocity fields is supporting an on-going effort with Dr. George Dossot and colleagues at the Naval Undersea Warfare Center Division Newport. Work was also done in FY14 in collaboration with Prof. Harry DeFerrari and Jennifer Wylie. The work done on improving the treatment of the bottom density discontinuity is an on-going effort with Dr. David J. Thomson in Canada. Elements of this work are anticipated to continue in FY15.

PUBLICATIONS

Smith, K.B., Upshaw, J.M., and Kubisak, T., "Observations of Horizontal Coupling in the Monterey Bay Canyon," Proc. Underwater Acoustics Intl. Conf. & Exhibition, 22-27 June, Rhodes, Greece, 2014.

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Tim Kubisak, "Investigation of Acoustic Vector Sensor Data Processing in the Presence of Highly Variable Bathymetry," M.S. Applied Physics (Acoustics), June, 2014.

Matthew Owens, "Comparison of Different Implementation Options for Density Discontinuity in Split-Step Fourier Parabolic Equation Models," M.S. Applied Science (Acoustics), March, 2014.

Jennifer Wylie, “The Effects of Random Bottom Bathymetry on Coherence in Shallow Water Acoustic Propagation,” Ph.D. Ocean Engineering (University of Miami), December, 2013.

Ahmed Helmy, “3-D Acoustic Scattering from 2-D Rough Surfaces Using a Parabolic Equation Model,” M.S. Engineering Acoustics, December, 2013.