

## **Analysis of 3-D Propagation Effects Due to Boundary and Volumetric Environmental Variability**

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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) scattering from two-dimensional (2-D) rough ocean surfaces. In collaboration with Dr. David Thomson (Canada), 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 rough surface scattering and bottom 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. In addition, the 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.

Additional work was also conducted to support the PhD research of Huikwan Kim at Univ of Rhode Island (in collaboration with Prof. Jim Miller and Prof. Gopu Potty), in which the MMPE model was used to include acoustic propagation in an atmospheric layer over the ocean surface. Work was also done in support of the PhD research of Jennie Wylie at the University of Miami (in collaboration with Prof. Harry Deferrari), and the PhD research of Justin Eickmeier at the University of Delaware (in collaboration with Prof. Mohsen Badiy).

# Report Documentation Page

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## 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. An implementation into a new version of MMPE was attempted (Smith, 2012), but later found to contain inconsistencies due to the interdependence of environmental depth dependence and azimuthal/cross-range field variability. 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 addition, the treatment of the bottom density discontinuity in split-step Fourier models was found to produce small phase errors at long range. Various alternative approaches were implemented in FY13 for comparison, as well as the development of the equations for a higher-order finite-difference approach to the density term. This latter approach also involves a hybrid split-step Fourier/finite-difference algorithm, similar to that originally developed by Yevick and Thomson (1997).

## RESULTS

### *3-D Rough Surface Scattering Studies:*

In FY12, the field equations corresponding to the displaced surface field transformation for rough surface scattering were derived in 3-D cylindrical and Cartesian coordinates (Smith, 2012). The form of these transformed equations were shown to be

$$\frac{\partial \tilde{\psi}}{\partial x} = -ik_0 (\tilde{T}_{op} + \tilde{U}_{op}) \tilde{\psi} \quad (1)$$

where the operators

$$\tilde{T}_{op} = \begin{cases} T_{3D} & , \quad z > \eta(x, y) \\ T_{3D} + \frac{i2}{k_0} \left[ \frac{\partial^2 \eta}{\partial x \partial y} (z - \eta) - \frac{\partial \eta}{\partial x} \frac{\partial \eta}{\partial y} \right] \frac{\partial}{\partial y} & , \quad z < \eta(x, y) \end{cases} \quad (2)$$

and

$$\tilde{U}_{op} = \begin{cases} U_{3D}(x, y, z) & , \quad z > \eta(x, y) \\ U_{3D}(x, y, -z + 2\eta(x, y)) - 2 \frac{\partial^2 \eta}{\partial x^2} (z - \eta) & , \quad z < \eta(x, y) \end{cases} \quad (3)$$

and the surface boundary is defined at depth  $z = \eta(x, y)$ . The cylindrical form is achieved simply by replacing  $x \rightarrow r$  and  $y \rightarrow r\phi$ .

The form of the operator  $\tilde{T}_{op}$  presents some challenges in implementation due to the additional differential term that must be applied over a variable rough surface. A hybrid split-step Fourier/finite-

difference scheme has been developed to address this in a new 3-D rough surface version of MMPE. Testing of this new algorithm is on-going, but some preliminary results are provided below.

As an initial test, a constant slope (smooth) surface was defined. Figure 1 represents the results from the cylindrical coordinate implementation. The upper 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 lower panel displays a depth slice in the TL field at 50 m depth (the source depth), which shows the interference pattern due primarily to the surface reflection. The shift in the interference pattern is consistent with what would be expected from a constant slope surface.

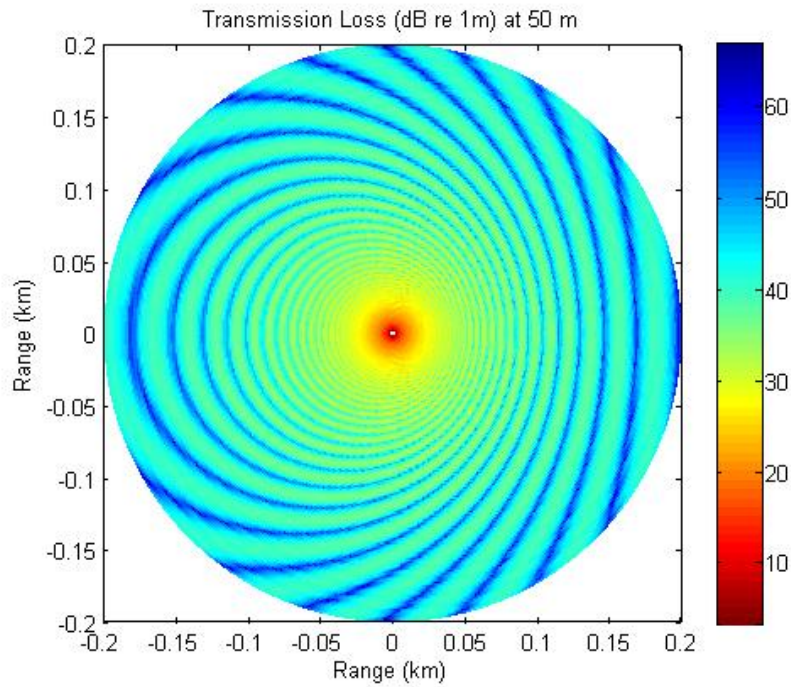
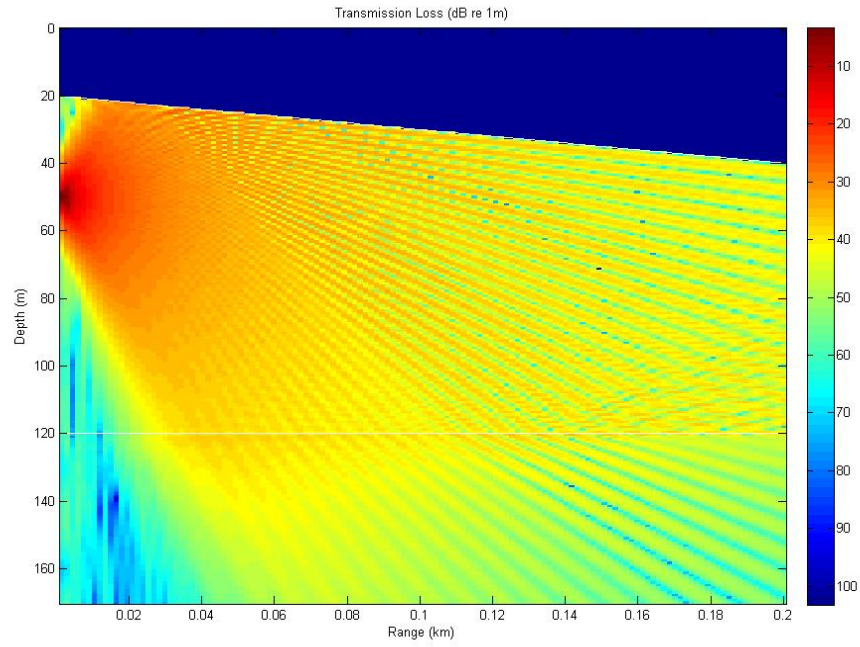
An additional test defined a single, planar (cross-range) sinusoidal depression in the surface. Figure 2 provides results from that test. Again, the upper panel displays the TL field along a single radial in the direction of the surface displacement. (The opposite radial shows a range-independent surface.) The lower 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.

The next phase of this work will be to compare these test case results with other models to begin confirming the accuracy of these results. More realistic surfaces will then be defined for general studies of 3-D surface scattering effects.

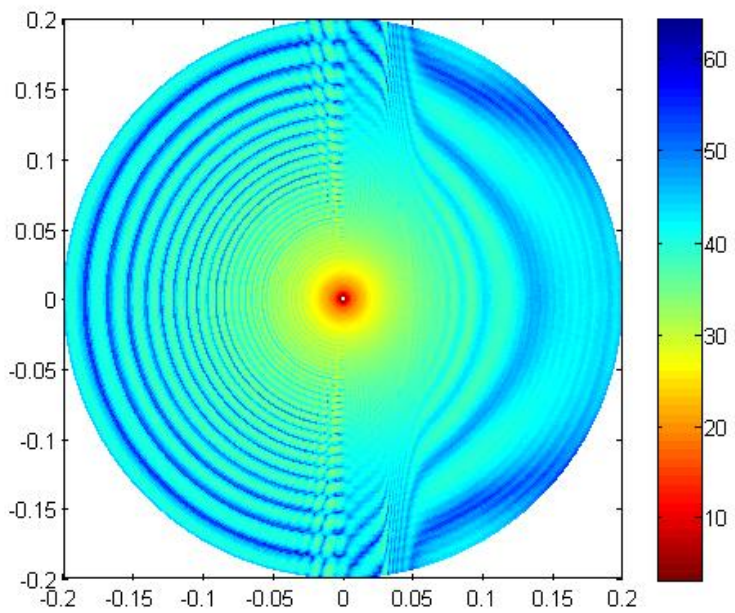
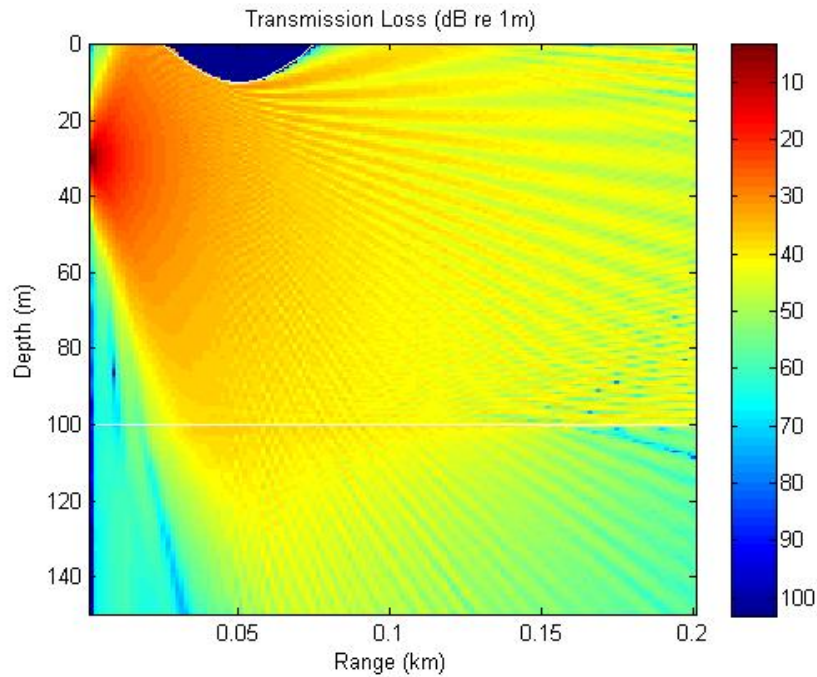
*Bottom Density Discontinuity Treatment:*

In FY13, the approach historically used in split-step Fourier algorithms to treat the density discontinuity at the water/bottom interface was found to introduce small phase errors that accumulated over long range. Near the end of FY13, I began collaborating with Dave Thomson (Canada) on investigations of this effect. We are currently in the process of assessing various techniques previously defined. In addition, I have developed higher-order finite-difference equations to employ in a hybrid split-step Fourier/finite-difference algorithm similar to that previously described by Yevick and Thomson (1997).

The next phase of this work will involve comparisons between several approaches, as well as comparisons with benchmark results. The goal is to determine the cause of this phase error, and to reduce or eliminate its impact on propagation models that utilize the split-step Fourier marching algorithm.



**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 (upper panel); TL field at a constant depth of 50 m (lower panel).**



***Figure 2: 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).***

**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 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.

## **RELATED PROJECTS**

The rough surface scattering work are on-going efforts done in collaboration with Dr. Mohsen Badiey and his colleagues at the Univ. of Delaware. The work on propagation in air/water/sediment is an on-going effort with colleagues at the Univ. of Rhode Island. The work done with MMPE to model rough bottom effects is an on-going effort with Prof. Harry Deferrari and colleagues at the Univ. of Miami. The work done on improving the treatment of the bottom density discontinuity is an on-going effort with Dr. David J. Thomson in Canada. All of this work is anticipated to continue in FY14.

## **REFERENCES**

- Yevick, D. and Thomson, D.J., "A hybrid split-step/finite-difference PE algorithm for variable-density media," *J. Acoust. Soc. Am.* 101, pp. 1328-1335, 1997.
- Smith, K.B., "Field transformational approach to three-dimensional scattering from two-dimensional rough surfaces," *J. Acoust. Soc. Am.* 131, pp. EL441-447, 2012.

## **PUBLICATIONS**

- Dossot, G.A., Badiey, M., Smith, K.B., Miller, J.H., Potty, G.R., and Lynch, J.F., "Evidence of escalating acoustic intensity preceding a strong internal wave event during the Shallow Water '06 experiment," *J. Acoust. Soc. Am.*, 2012 [submitted].