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Abstract: Over the past several years, many acoustic propagation models have been adapted to compute the influence of azimuthal coupling. These so-called 3-D models should provide more accurate predictions of the acoustic field in 3-D variable environments than previous Nx2-D models. However, such advanced 3-D propagation models are generally slower than their Nx2-D predecessors. It is, therefore, important to understand the significance of the difference between 3-D and Nx2-D and when such effects should be considered. Furthermore, as of this date, no formal set of benchmark cases and solutions has been defined to test the accuracy of the various 3-D models currently being used. This paper will provide a general overview of 3-D propagation models and how they can be used to assess the significance of azimuthal coupling in ocean acoustics. Specific examples of such influences will be provided from a 3-D parabolic equation model and compared to results from the corresponding Nx2-D version. Of particular interest will be the pseudo-3-D effects predicted by Nx2-D calculations and the ability to distinguish true 3-D effects in experimental data. Finally, several environmental scenarios will be suggested as possible benchmark cases for future studies. [This work sponsored by ONR Code 321OA.]

MODELING 3-D PROPAGATION

The earliest types of acoustic propagation models dealing with spatial variability of the environment were based on ray theoretic approaches. Not surprisingly, ray models were also the first to be adapted to handle three-dimensionally varying ocean environments (Weston, 1961). However, it is well known that ray models can suffer from severe limitations such as the inability to correctly predict the influence of diffraction, singularities encountered near caustics, and effects of chaos over long ranges. Despite these limitations, ray models remain widely used to study 3-D propagation effects.

Full-wave, finite frequency models such as 3-D coupled modes (e.g., Chiu and Ehret, 1990) overcome the problems associated with rays but can be computationally intensive in strongly varying environments. As in the 2-D propagation problem, many investigators have turned to parabolic approximation methods (Tappert, 1977) in order to produce efficient prediction algorithms (e.g., Siegmann et al., 1985, and Lee et al., 1992). The incorporation of recent advancements in the phase and wide-angle accuracy of PE models would suggest that these approaches are optimal in terms of accuracy and efficiency in general, 3-D variable ocean environments.

Such 3-D PE models can still be quite computationally intensive, however, not only in the calculation of the propagating field but also in the interface with and interpolation of large, 3-D data bases. Furthermore, none of the aforementioned 3-D models has been compared to analytical benchmark solutions primarily because such analytical solutions do not exist for any but the most ideal 3-D environments. It is, therefore, difficult to speculate on the accuracy of any 3-D propagation model or the results computed for a wide variety of real world problems.

One of the most commonly used environments for testing these models is the 3-D wedge. Buckingham (1984) has provided a theoretical solution for the 3-D wedge with perfectly reflecting boundaries but this bears little resemblance to the real ocean and is not amenable to some models which assume a penetrable bottom. Westwood (1992) and Deane and Buckingham (1993) have also developed theoretical solutions to the penetrable wedge which is a more realistic candidate for producing benchmark solutions. But this is still a very idealized environment and no such theoretical solution will exist for the majority of realistic, 3-D ocean environments.

Comparisons with experimental results are even more difficult with the possible exception of very long range propagation problems where 3-D influences are most obvious (e.g., Heaney et al., 1991). Part of the difficulty is our ability to distinguish differences between 3-D and Nx2-D from differences due to errors in environmental inputs or unknown environmental variability. In addition, Nx2-D models can predict propagation effects that appear remarkably 3-D in the presence of 3-D environmental variations. For example, Doolittle et al. (1993) claimed to experimentally confirm horizontal refraction in a shallow water environment near the East Australian Continental Slope by analyzing the angle of arrival on a horizontal array. However, they failed to distinguish this from the same type of effect predicted by Nx2-D models. In other words, in a 3-D variable environment, even Nx2-D models will predict *non-direct path arrivals*. As mentioned, uncertainties in the environment make direct confirmation of 3-D effects in their data extremely difficult.

Glegg et al. (1993) attempted to overcome this problem by comparing some of the aforementioned theoretical solutions for the 3-D wedge with data taken from a carefully controlled tank experiment. This is perhaps the most convincing experimental result exhibiting horizontal refraction over relatively short ranges and relies on the mode cut-off with range to discriminate it against Nx2-D effects (which do not predict ranges of mode cut-off). Still, this is only one scenario and is not amenable to all 3-D propagation models.

It is possible (and quite likely) that future benchmarking will require a hierarchy of methods and models. Beginning with the simplest of environments for which there are analytical solutions, we may confirm the predictions of one (or a small number of) numerical propagation model. By altering this environment in some way (which precludes the use of the analytical solution), we may be able to expand the benchmarking to include other models. Once these other models are producing convincingly accurate solutions, more general ocean environments may be treated. Naturally, we must be cautious with such an approach and appeal to real data whenever possible. An excellent overview of current issues in 3-D propagation has been provided by Tolstoy (1996).

The general form of the parabolic approximation to the wave equation for the acoustic pressure $p(r,z)$ is

$$P_{op}u = ik_0 Q_{op}u \quad \text{where } p(r,z) = \frac{1}{\sqrt{r}}u(r,z),\ P_{op} = \frac{\partial}{\partial r}, \text{ and } Q_{op} = \left(n^2 + \frac{1}{k_0^2}\frac{\partial^2}{\partial z^2} + \frac{1}{r^2 k_0^2}\frac{\partial^2}{\partial \varphi^2}\right)^{1/2}. \tag{1}$$

Baer (1981) was the first to implement a fully 3-D PE algorithm in order to study propagation through a mesoscale eddy. However, he approximated the pseudo-differential operator Q_{op} by the leading order terms of a binomial expansion, consistent with the so-called "standard PE" approximation in both depth and azimuth. More recently, Smith (1996) applied the "wide-angle PE" approximation of Thomson and Chapman (1983) to both the depth and azimuthal differential terms in Q_{op} thereby allowing more accurate solutions at larger angles in depth and azimuth. Unfortunately, this leads to an MxN (depth x azimuth) matrix operator which is memory intensive. By assuming that horizontal refraction effects will be small, a binomial expansion can be made with respect to the azimuthal coupling term, thereby separating the depth and azimuthal operators. This leads to the approximate form

$$Q_{op} \approx 1 + \frac{\partial^2}{\partial z^2}\left[\left(1 + \frac{\partial^2}{\partial z^2}\right)^{1/2} + 1\right]^{-1} + \frac{1}{2k_0^2 r^2}\frac{\partial^2}{\partial \varphi^2} + (n-1). \tag{2}$$

For this work, Eqs. (1) and (2) are solved via a split-step Fourier algorithm. Environments to be examined are the 3-D penetrable wedge, a 3-D penetrable ridge, a 3-D seamount, and a realistic 3-D environment near the shelf break of the Mid-Atlantic Bight. While extreme scenarios of the first three environments will be suggested as benchmark cases, the final case examines the influence of horizontal refraction in real, shallow water environments. What is emphasized is not the absolute 3-D effects of the propagation but rather the difference between what is predicted by the fully 3-D model and its corresponding Nx2-D approximation. It will be shown that in many cases, the Nx2-D approach can adequately predict 3-D propagation effects, including apparent horizontal refraction.

REFERENCES

(1) Baer, R. N., *J. Acoust. Soc. Am.* **69**, 70-75 (1981).

(2) Buckingham, M. J., "Acoustic propagation in a wedge-shaped ocean with perfectly reflecting boundaries," in *Hybrid Formulation of Wave Propagation*, ed. L. B. Felsen (Nijhoff, Dordrecht, 1984).

(3) Chiu, C.-S. and Ehret, L. L., "Computation of sound propagation in a three-dimensionally varying ocean: A coupled normal mode approach," in *Computational Acoustics: Ocean-Acoustic Models and Supercomputing*, ed. Lee et al. (North-Holland, Amsterdam, 1990).

(4) Deane, G. B. and Buckingham, M. J., *J. Acoust. Soc. Am.* **93**, 1319-1328 (1993).

(5) Doolittle, R., Tolstoy, A., and Buckingham, M. J., *J. Acoust. Soc. Am.* **83**, 2117-2125 (1988).

(6) Glegg, S. A. L., Deane, G. B., and House, I. G., *J. Acoust. Soc. Am.* **94**, 2334-2342 (1993).

(7) Heaney, K. D., McDonald, B. E., and Kuperman, W. A., *J. Acoust. Soc. Am.* **90**, 2586-2594 (1991).

(8) Lee, D., Botseas, G., and Siegmann, W. L., *J. Acoust. Soc. Am.* **91**, 3192-3202 (1992).

(9) Siegmann, W. L., Kriegsmann, G. A., and Lee, D., *J. Acoust. Soc. Am.* **78**, 659-664 (1985).

(10) Smith, K. B., "Modeling the effects of azimuthal coupling on acoustic propagation in the presence of 3-dimensional, rough ocean interfaces using the parabolic approximation," in *Special Issue of Theoretical and Computational Acoustics*, eds. Lee et al., 115-131 (World Scientific Publishing Co., 1996).

(11) Tappert, F. D., "The parabolic equation method," in *Wave Propagation and Underwater Acoustics*, ed. J. B. Keller and J. Papadakis, 224- 286 (Springer-Verlag, New York, 1977).

(12) Thomson, D. J. and Chapman, N. R., *J. Acoust. Soc. Am.* **74**, 1848-1854 (1983).

(13) Tolstoy, A., "3-D propagation issues and models," *J. Comp. Acoust.* **4**, 243-271 (1996).

(14) Weston, D. E., *Proc. Phys. Soc. London* **78**, 46-52 (1961).

(15) Westwood, E. K., *J. Acoust. Soc. Am.* **92**, 2212-2222 (1992).