

**Final Technical Report
for
Office of Naval Research
Award Number N000140710895**
Scientific Officers: Dr. E. S. Livingston, Dr. D. B. Reeder

Special Research Award in Ocean Acoustics
Efficient Determination of Three-Dimensional Acoustic Fluctuations
in Shallow-Water Waveguides
Principal Investigator: Dr. William L. Siegmann
Doctoral Student Co-Principal Investigator: Mr. Stephen V. Kaczkowski
Rensselaer Polytechnic Institute
110 Eighth Street
Jonsson-Rowland Science Center 1C08
Troy, New York 12180-3590
phone: (518) 276-6905 fax: (518) 276-2825 email: siegmw@rpi.edu

I. SUMMARY

This is the Final Technical Report for ONR Award Number N000140710895, which commenced on 16 April 2007, received a no-cost extension on 1 January 2009, and terminated on 30 September 2009. This is a Special Research Award in Ocean Acoustics to provide doctoral student funding to Mr. Stephen V. Kaczkowski.

During the performance period, Mr. Kaczkowski completed all PhD requirements except his thesis and thesis defense. He is on track to complete his thesis and defense by July 2010 and obtain his PhD in August 2010. In his case, the duration of his Award does not coincide with the time to degree completion. Since he entered Rensselaer Polytechnic Institute as a doctoral student in August 2005, his degree completion time will be five years. Therefore, he can finish his degree in a few months less than the average completion time for doctoral students in the Department of Mathematical Sciences.

The major results of his research are indicated in Section II. Presentations are indicated in Section III. The publication plan for his results is indicated in Section IV

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II. RESEARCH RESULTS

1. Convenient approximations for higher acoustic modes

- Many shallow water waveguides have sound speed profiles that are small deviations from isospeed, so that perturbation methods can be applied to obtain approximate formulas which are valid for modes and parameter values of interest. We develop two-term asymptotic modal formulas that are concise and more convenient than numerical or series representations. The formulas are designed to be useful for determining parameter dependences of relevant acoustic quantities. The main restrictions are to propagating modes, to assuming range dependence is negligible or adiabatic, and to fast isospeed bottoms with sound speed c_b exceeding the maximum water sound speed c_h . The perturbation parameter is the relative difference of c_h and a reference water speed.
- The approach uses the modified, or generalized, Green's function. Solution formulas are compared with those from variation of parameters and resolvent kernel methods [1]. The primary ocean waveguide environments considered have thermocline sound speed profiles with isospeed layers above and below a middle layer of decreasing sound speed. Comparisons of the formulas are made with numerical calculations over a range of frequencies and mode numbers. The results [2] show that the approximations are accurate for modes with phase speed v_n higher than c_h , and that accuracy improves as mode number increases and as depth in wavelength decreases.

2. Improved approximations for higher acoustic modes

- Classical WKBJ approximations of acoustic modes have been used to show the relationships between different modal expressions and to approximate acoustic field quantities efficiently. A modified version is developed, which unlike the original version, does not have singularities at any depth in the water column. This is because the argument of the oscillatory terms is simplified. Modal formulas from the method are shown to be convenient and useful for demonstrating the dependence on operational and environmental parameters such as frequency, channel depth, and water and sound speed parameters.
- The restrictions are basically the same as for the approach in [2]. However, larger sound speed gradients are treated, along with other profiles including linear downward refracting. Analytic and numerical results demonstrate how parameter changes quantitatively affect the modes and properties including cutoff frequency, phase velocity, group velocity, and the maximum number of propagating modes [3]. The accuracy of the approximation in frequency and mode number is illustrated using comparisons with benchmarks, for examples with two shallow water environments. As before the accuracy improves as mode number increases and as depth in wavelength decreases.

3. Convenient approximations for lower modes

- Accurate and convenient approximations are needed when modal phase speed v_n falls below c_h , which can occur for lower modes, especially at higher frequencies. Another asymptotic procedure using Airy functions permits a new set of modal expressions. This development is based on work of Langer which is extended for shallow water waveguide applications.
- Results from the formulas show unexpected results for environments with nonzero sound speed gradients at the water sediment interface. For cases such as a linear downward refracting profile, the modal amplitude at the water sediment interface approaches a constant for high frequencies. In contrast, for environments that are upward refracting in the lower water channel, the interfacial modal amplitude decreases exponentially with frequency [4]. These variations are useful in explaining and predicting the behavior of the modal attenuation coefficients, for example. The validity of the approximations can again be summarized in frequency-mode number plots. However, in contrast to the higher mode approximations, the accuracy improves as mode number decreases and as depth in wavelength increases.

4. Parametric dependence of modal attenuation coefficients

- The frequency dependence of modal attenuation coefficients (MACs) is critical for explaining and predicting the overall range behavior of transmission loss. In addition the MACs have a major role in specifying the propagation influence of poro-elastic sediments. Using our modal approximations, expressions for MACs are derived which demonstrate their dependence on parameters such as frequency, mode number, and water column and bottom sound speeds. Sandy-silty sediments along with nonlinear frequency dependence of intrinsic attenuation are assumed in the upper sediment layer. Intrinsic attenuation is taken to be the main loss mechanism, so that boundary and scattering losses are neglected. Ocean sound speed profiles that have portions which are upward refracting, isospeed, and downward refracting are considered.
- The behavior of MACs is strongly sensitive to characteristics of the water sound speed profile. The gradient at the water-sediment interface turns out to have a critical effect on the frequency dependence [5]. For environments with a negative (downward refracting) gradient there, the MACs for modes with $v_n < c_h$ increase like f^{m-1} , where m is the frequency power-law exponent of sediment attenuation. The exponent $m \sim 1.8$ for sandy silty sediments and frequencies in the 50 – 2000 Hz band. For environments with a positive (upward refracting) gradient at the sediment interface, the MACs decrease exponentially with increase frequency. Large values of modal attenuation at higher mode numbers due to energy trapped in an upper sediment layer are also explained from our formulas.

5. Modal attenuation effects on transmission loss

- Since transmission loss in ocean waveguides is a key sonar parameter, for decades it has been a focus of attention for system applications. In waveguides that have relatively weak range dependence, the intrinsic sediment attenuation controls overall loss behavior through the MACs of the propagating modes. Our earlier results can be applied for this understanding this process and for interpreting experimental observations from multiple locations. The approach is to derive an expression for an averaged transmission loss that is reduced from cylindrical spreading and is independent of two operational parameters, source and receiver depth. The value of this quantity is shown by describing how changes in environmental parameters (particularly, thermocline strength and depth) which affect modal attenuation produce corresponding changes in the loss field.
- Using our expression for averaged loss, we devise a method for determining the number of modes that contribute effectively to the total loss field. Convenient loss expressions for Pekeris waveguides are developed using high frequency approximations for the MAC of mode n in the form an^2 , which is valid for ranges less than $(8a)^{-1}$ m. The loss expressions have several terms, each one having a natural physical interpretation. The new expression may be compared term by term with a very widely known result for transmission loss obtained by Rogers in 1983 using ray theory arguments. The two expressions have the same parameter dependence, which provides a striking modal foundation for Rogers' result [6]. Other loss characteristics may be conveniently extracted as well.

III. PROFESSIONAL PRESENTATIONS

- S. V. Kaczkowski, "Modal approximations in shallow water," ocean acoustics seminar, Woods Hole Oceanographic Institution, Woods Hole, MA (December 2006).
- S. V. Kaczkowski, W. L. Siegmann, A. D. Pierce, and W. M. Carey, "Mode formulas for shallow water waveguides using a modified asymptotic approximation," *154th Meet. Acoust. Soc. Am.*, New Orleans, (A) *J. Acoust. Soc. Am.* **122**, 2942 (2007).
- S. V. Kaczkowski, W. L. Siegmann, W. M. Carey, A. D. Pierce, and W. Saintval, "Relationships between intrinsic sediment attenuation, modal attenuation, and transmission loss in experiments over sandy-silty sediments," *158th Meet. Acoust. Soc. Am.*, San Antonio, (A) *J. Acoust. Soc. Am.* **126**, 2167 (2009).

IV. PUBLICATION PLAN

- [1] A. D. Pierce, W. M. Carey, W. L. Siegmann, S. V. Kaczkowski, and W. Saintval, "Analytic solution for guided waves in a canonical model of shallow water with a thermocline," *Proc. IEEE Oceans 06 Conf.*, Boston, DOI306891, 7 pp. (2006).
- [2] S. V. Kaczkowski, A. D. Pierce, W. M. Carey, and W. L. Siegmann, "Modal approximations in shallow water," *Proc. IEEE Oceans 07 Conf.*, Aberdeen, DOI4302472, 6 pp. (2007).
- [3] S. V. Kaczkowski, W. L. Siegmann, A. D. Pierce, and W. M. Carey, "Modal approximations for high mode numbers," to be submitted to *J. Comp. Acoust.*
- [4] S. V. Kaczkowski, W. L. Siegmann, A. D. Pierce, and W. M. Carey, "Mode formulas for shallow water waveguides using a modified asymptotic approximation," to be submitted to *Wave Motion*.
- [5] S. V. Kaczkowski, W. L. Siegmann, W. Saintval, A. D. Pierce, and W. M. Carey, "Parametric variations of modal attenuation coefficients obtained from modal approximations," to be submitted to *J. Acoust. Soc. Am.*
- [6] S. V. Kaczkowski, W. M. Carey, A. D. Pierce, and W. L. Siegmann, "Intrinsic sediment attenuation, modal attenuation, and transmission loss in experimental environments with sandy-silty sediments," to be submitted to *J. Ocean. Eng.*

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