

## **Final Technical Report**

**Office of Naval Research - Award Number N000140310238**

Scientific Officers: Dr. E. S. Livingston, Dr. D. B. Reeder

### **Special Research Award in Ocean Acoustics**

**Transmission Loss and Signal Coherence in Shallow Water Waveguides**

Principal Investigator: Dr. William L. Siegmann

Student Co-Principal Investigator: Dr. Wendell J. Saintval (Ph.D. August 2008)

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](mailto:siegmw@rpi.edu)

## **I. SUMMARY**

This is the Final Technical Report for ONR Award Number N000140310238, which commenced on 01 January 2003, received a no-cost extension on 31 December 2005, and terminated on 30 September 2006. This grant is a Special Research Award in Ocean Acoustics to provide doctoral student funding to Wendell Saintval.

During the performance period of the Award, Wendell Saintval finished all PhD requirements except his thesis and thesis defense. He completed those and obtained his PhD in August 2008 under the co-supervision of his two thesis advisors, Dr. William L. Siegmann (Rensselaer) and Dr. William M. Carey (Boston University). He is currently employed as a Postdoctoral Associate in the Acoustics Division, Naval Research Laboratory, Washington, DC.

The overall objectives of his research are in Section II, and a summary of major results is provided in Section III. Presentations are listed in Section IV, and the publication plan for his results is indicated in Section V.

## **II. OBJECTIVES**

The first goal of this project is to determine how properties of the intrinsic upper-sediment attenuation influence the acoustic field at low frequencies using a recent simplification of the Biot model. The second goal of this research is to understand the environmental influences on modal attenuation coefficients (MACs) and transmission loss observed in experiments on the New Jersey Continental Shelf (1988, 1993) and in the Gulf of Mexico (1970) and to compare model calculations with experimental data.

**20100823061**

**REPORT DOCUMENTATION PAGE**

Form Approved  
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to the Department of Defense, Executive Service Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

**PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.**

<b>1. REPORT DATE (DD-MM-YYYY)</b> 16-08-10		<b>2. REPORT TYPE</b> Final Technical		<b>3. DATES COVERED (From - To)</b> 1 Jan 2003 - 30 Sept 2006	
<b>4. TITLE AND SUBTITLE</b> Special Research Award: Ocean Acoustics Traineeship  Transmission Loss and Signal Coherence in Shallow Water Waveguides				<b>5a. CONTRACT NUMBER</b>	
				<b>5b. GRANT NUMBER</b> N000140310238	
				<b>5c. PROGRAM ELEMENT NUMBER</b>	
<b>6. AUTHOR(S)</b> Siegmann, William L.  Saintval, Wendell J.				<b>5d. PROJECT NUMBER</b>	
				<b>5e. TASK NUMBER</b>	
				<b>5f. WORK UNIT NUMBER</b>	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> Rensselaer Polytechnic Institute 110 Eighth Street Troy, NY 12180-3590				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> Office of Naval Research 875 North Randolph Street Arlington, VA 20210-2109				<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b> ONR	
				<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b>	
<b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b> Approved for Public Release; distribution is Unlimited.					
<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b> This is the Final Technical Report of ONR Award Number N000140310238. During the performance period, Dr. Saintval was supported for research toward his PhD. The overall objectives of the research are in Section II, and a summary of major results is provided in Section III. Presentations are listed in Section IV, and the publication plan for results is indicated in Section V.					
<b>15. SUBJECT TERMS</b> acoustic propagation, shallow water, sound speed profile variations, normal modes, modal attenuation coefficient, frequency and parameter sensitivity, transmission loss, experimental data comparisons.					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>	<b>18. NUMBER OF PAGES</b>	<b>19a. NAME OF RESPONSIBLE PERSON</b>
<b>a. REPORT</b>	<b>b. ABSTRACT</b>	<b>c. THIS PAGE</b>			William L. Siegmann
U			UU	6	<b>19b. TELEPHONE NUMBER (Include area code)</b> (518) 276-6905

### III. RESEARCH RESULTS

1. A recent simplification of Biot theory is used to illustrate relationships between the intrinsic sediment attenuation and the attenuation of individual modes, expressed by the modal attenuation coefficients (MACs). The simplest two-layer isospeed waveguides yield MACs that decrease from  $f^{-2}$  to  $f^{-1}$  as frequency  $f$  becomes large. A heuristic modification of these waveguides is designed to suggest how changes arise in their magnitude and frequency behavior [1]. We show how they increase with incorporation of a fluid-saturated porous layer in the waveguide by using a convenient parameterization and numerical results. The frequency power-law behavior that is observed increases from  $f^{0.7}$  to  $f^{1.7}$  as the thickness of this layer increases from 2 to 15% of the water depth.
2. A proceedings publication is concerned with the general problem of obtaining analytical information about the modal profiles and eigenvalues for a class of shallow water sound speed and density profiles [2]. The real part of an eigenvalue is related to the horizontal phase speed of the mode, and the imaginary part is related to the MAC. The mean waveguide is a Pekeris model, for which the sound speed in the water column is constant and the bottom is taken to be homogenous. The water sound speed is assumed to decrease monotonically with depth and to be everywhere less than the bottom sound speed. The principal interest is when the water column sound speed variation is relatively small. Several perturbation approaches for obtaining the modal depth profiles and the associated eigenvalues are discussed and compared.
3. The importance of the MACs for waveguide propagation strongly implies that useful approximations for them are needed. One such expression is developed for depth-dependent sound speed profiles over sandy-silty sediments with nonlinear frequency dependence of intrinsic attenuation [3]. This formula is novel in its expression in terms of parameters of the upper sediment layer. A key result is that the MAC frequency dependence has unexpectedly large changes as profiles vary from isospeed to downward refracting conditions. For example, as the sound speed at the water surface increases by just 5 m/s over the isospeed case, the MAC frequency power-law exponent changes from -0.93 to 1.0 in the 1500 to 2000 Hz frequency band. At high frequencies and mode numbers, the MACs eventually decrease because of less energy penetrating the bottom.
4. The critical step in demonstrating the usefulness of our results is applying them to environments of experimental and operational interest. The magnitude and frequency dependence of MACs up to 2 kHz are calculated for waveguides with isospeed, linear, and thermocline-type piecewise linear water sound speed profiles over sandy-silty bottoms [4]. These waveguides represent principal features of experimental environments near the New Jersey continental shelf. We include a quadratic frequency-dependent intrinsic attenuation in a thin upper sediment layer. As the upper sediment layer thickness increases, the MACs for waveguides with profile gradients

near the bottom interface show increased magnitude, reordering of least-attenuated modes, and frequency-behavior transition from roughly  $f^{-2}$  to  $f^1$ .

5. The frequency dependence of modal attenuation coefficients (MACs) is very important for explaining and predicting the overall range behavior of transmission loss. New modal approximations are obtained and used to derive expressions for MACs which demonstrate their dependence on parameters such as frequency, mode number, and water column and bottom sound speeds. Ocean sound speed profiles that have portions which are both upward and downward refracting and isospeed are considered. The gradient at the water-sediment interface has a critical effect on the frequency dependence [5]. For environments with a downward refracting gradient at the interface, the MACs for low modes typically increase like  $f^{0.8}$  for Biot-type intrinsic sediment attenuation. For environments with an upward refracting gradient at the sediment interface, the MACs decrease exponentially with increased frequency. Large values of modal attenuation at higher mode number due to energy trapped in an upper sediment layer are also explained from our formulas.
6. Data and parameters from a shallow water Gulf of Mexico environment with a sandy depositional bottom are used for a test of our approach. Ingenito performed measurements and used data fitting to infer that individual MACs decrease with frequency  $f$  and intrinsic sediment attenuation increases roughly as  $f^{1.75}$ . A collection of water sound speed profiles were measured which include upward and downward refracting and nearly isospeed cases. Numerical results from our formulas using a two-layer waveguide are compared with the previously deduced MACs. Good agreement was found with the weakly downward refracting and nearly isospeed profiles [6]. Comparisons with the reportedly most reliable experimental results showed very good agreement except for cases with upward and strongly downward refracting profiles.
7. It is valuable for propagation calculations to obtain improved geoacoustic depth profiles in normally consolidated poro-elastic upper sediment layers. A technique for obtaining such profiles, developed by Cederberg, is enhanced by using LambertW function approximations of the environmental parameters [7]. The results are more realistic than linear sound speed profiles in the upper sediment layer and are appropriate for typical sandy shallow water bottoms. Parameter sensitivities are assessed for upper layer depth profiles of sound speed, porosity, and attenuation.
8. The rate of increase of range-window averaged transmission loss with range, reduced to eliminate the effect of cylindrical spreading, is conveniently measured by an effective attenuation coefficient. Evans and Carey showed the relation between this quantity and the MAC when one propagating mode dominates. We focus on the interesting connections between these quantities for downward refracting profiles at low frequencies [8]. For example, with isospeed water over an upper sediment layer with Biot-type quadratic frequency dependence of attenuation, the effective attenuation coefficient increases slowly with frequency to about 1 kHz and then remains roughly constant. A strikingly different situation occurs when the water sound speed has a downward refracting constant gradient profile. The MACs have minima with

frequency, the number of the least attenuated mode increases, and a band of modes that causes the overall TL increase typically shifts toward higher mode numbers. As a consequence the effective attenuation coefficient increases roughly linearly with frequency.

**NOTE:** No patent applications were prepared under this project.

#### IV. PROFESSIONAL PRESENTATIONS

- 1) W. Saintval, W. L. Siegmann, W. M. Carey\*, A. D. Pierce, and J. F. Lynch, "Dependence of modal attenuation coefficient frequency variation on upper sediment attenuation," *149<sup>th</sup> Meet. Acoust. Soc. Am.*, Vancouver, BC, (A) *J. Acoust. Soc. Am.* **117**, 2496 (2005).
- 2) W. Saintval\*, W. L. Siegmann, W. M. Carey, A. D. Pierce, and J. F. Lynch, "Influence of intrinsic sediment attenuation on the propagation of sound in shallow water," *Fifth Walter Lincoln Hawkins Grad. Res. Conf.*, Rensselaer Poly. Inst., Troy, NY (Oct. 2005).
- 3) W. Saintval\*, W. L. Siegmann, W. M. Carey, A. D. Pierce, and J. F. Lynch, "Analysis of acoustic influence of frequency variation in an upper-sediment model," *SIAM Ann. Meet.*, Boston, MA (July 2006).
- 4) W. Saintval\*, W. L. Siegmann, W. M. Carey, J. D. Holmes, and A. D. Pierce, "Sensitivity of modal attenuation coefficients to environmental parameters," *IEEE/MTS OCEANS '06 Conf.*, Boston, MA (Sept. 2006).
- 5) A. D. Pierce\*, W. M. Carey, W. L. Siegmann, S. V. Kaczowski, and W. Saintval, "Analytical solution for guided waves in a canonical model of shallow water with a thermocline," *IEEE/MTS OCEANS '06 Conf.*, Boston, MA (Sept. 2006).
- 6) W. Saintval\*, "Parameter sensitivities of modal attenuation coefficients in models for shallow water environments," *Rosensteil School Marine Atmos. Scis.*, Miami, FL (Jan. 2007) (invited).
- 7) W. Saintval\*, W. M. Carey, A. D. Pierce, J. F. Lynch, and W. L. Siegmann, "Frequency variability of modal attenuation coefficients," *153<sup>rd</sup> Meet. Acoust. Soc. Am.*, Salt Lake City, UT, (A) *J. Acoust. Soc. Am.*, **121**, 3076 (2007).
- 8) W. Saintval\*, W. L. Siegmann, W. M. Carey, and A. D. Pierce, "Environmental effects on frequency behavior of modal attenuation coefficients for sandy bottoms," *155<sup>th</sup> Meet. Acoust. Soc. Am.*, Paris, France, (A) *J. Acoust. Soc. Am.*, **123**, 3594 (2008).
- 9) S. V. Kaczowski\*, 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," *158<sup>th</sup> Meet. Acoust. Soc. Am.*, San Antonio, TX (A) *J. Acoust. Soc. Am.*, **126**, 2167 (2009).

\* Paper Presenter

## V. PUBLICATION PLAN

- [1] W. J. Saintval, W. L. Siegmann, W. M. Carey, A. D. Pierce, and J. F. Lynch, "A modified Pekeris waveguide for examining sediment attenuation influence on modes," submitted to *J. Comp. Acoust.*
- [2] A. D. Pierce, W. M. Carey, W. L. Siegmann, S. V. Kaczowski, and W. Saintval, "Analytic solution for guided waves in a canonical model of shallow water with a thermocline," *Proc. IEEE Oceans 06 Conf.*, Boston, MA, DOI306891, 7 pp. (2006).
- [3] W. Saintval, W. L. Siegmann, W. M. Carey, J. D. Holmes, and A. D. Pierce, "Sensitivity of modal attenuation coefficients to environmental parameters," *Proc. IEEE/MTS OCEANS '06 Conf.*, Boston, MA, DOI306872, 3 pp. (2006).
- [4] W. J. Saintval, W. L. Siegmann, W. M. Carey, A. D. Pierce, and J. F. Lynch, "Frequency variability of modal attenuation coefficients," to be submitted to *J. Acoust. Soc. Am. Expr. Let.*
- [5] S. V. Kaczowski, W. L. Siegmann, W. J. 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. Expr. Let.*
- [6] W. J. Saintval, W. L. Siegmann, W. M. Carey, and A. D. Pierce, "Parameter sensitivities of modal attenuation coefficients for sandy sediments in the Gulf of Mexico," to be submitted to *J. Acoust. Soc. Am. Expr. Let.*
- [7] W. J. Saintval, W. L. Siegmann, W. M. Carey, A. D. Pierce, and J. F. Lynch, "Frequency variation in upper sediment layer geoacoustic profiles," to be submitted to *IEEE J. Ocean Eng.*
- [8] W. J. Saintval, W. L. Siegmann, W. M. Carey, A. D. Pierce, and J. F. Lynch, "Estimation of effective attenuation coefficients in NJ Shelf environment," to be submitted to *J. Acoust. Soc. Am.*