

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 29 Jun 1998	3. REPORT TYPE AND DATES COVERED Final Technical Report	
4. TITLE AND SUBTITLE Numerical Studies of Rough Surface Scattering Models		5. FUNDING NUMBERS N00014-89-J-1989	
6. AUTHOR(S) Shira L. Broschat		8. PERFORMING ORGANIZATION REPORT NUMBER 11F-3820-2560	
7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES) School of Electrical Engineering & Computer Science Washington State University PO Box 642752 Pullman, WA 99164-2752		10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAMES(S) AND ADDRESS(ES) Office of Naval Research, Code 3210A 800 North Quincy Arlington, VA 22217-5000		11. SUPPLEMENTARY NOTES	
a. DISTRIBUTION / AVAILABILITY STATEMENT Unlimited		12. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) This final technical report summarizes the results of work performed between 1 Sep 89 and 31 Mar 97 or accomplishments achieved as a result of this work. Finite-Difference Time-Domain code was developed for rough surface scattering. The phase perturbation, small slope approximation, local parabolic approximation, and nonlocal small slope approximation models for rough surface scattering were developed and examined for a number of different spectra and surface types.			
14. SUBJECT TERMS rough surface scattering, small slope approximation, phase perturbation, local parabolic approximation, nonlocal SSA, FDTD		15. NUMBER OF PAGES 4	
17. SECURITY CLASSIFICATION OF REPORT Unclassified		16. PRICE CODE	
18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL	

19980707 165

ONR FINAL TECHNICAL REPORT

Title: Numerical Studies of Rough Surface Scattering Models

Grant No.: N00014-89-J-1989

PI: Shira L. Broschat

I. Summary

The focus of this research has been the development of analytic surface scattering models that accurately predict acoustic wave scattering from sea surfaces and from the ocean bottom. A number of surface scattering models have been developed and examined. For the phase perturbation approximation we obtained scattering strength results for 2-D pressure-release surfaces with a Gaussian spectrum and for 1-D pressure-release surfaces with a Pierson-Moskowitz spectrum. Results were also obtained for the coherent reflection loss. For the small slope approximation we derived the expressions for the coherent reflection coefficient and for the first three terms of the incoherent bistatic scattering cross section. In addition, we thoroughly examined and explained small slope theory. Numerical results for the scattering strength were obtained for both 1-D and 2-D pressure-release surfaces using a Gaussian spectrum or a Pierson-Moskowitz spectrum, and results were obtained for the coherent reflection loss. Fluid-solid and fluid-fluid interface problems were also studied. Expressions for the cross section were derived, and numerical results for the scattering strength were obtained for 1-D surfaces for the lowest-order small slope approximation using both Gaussian and modified power-law spectra. The local parabolic approximation was developed, and numerical results for the scattering strength were presented for pressure-release surfaces. Our most recent work has focused on the nonlocal small slope approximation which was developed, in part, as a result of our study of the small slope approximation. While the majority of the research accomplished under this grant concerned the study of analytic models, a numerical model was developed as well. This numerical model was based on the Finite-Difference Time-Domain (FDTD) method, and it was developed for two purposes: To benchmark approximate analytic models and for use in conjunction with another ONR-sponsored project to study acoustic propagation in a shallow-water environment.

II. Conference Papers (P), Proceedings (Pr), and Digests (D):

- [1] Broschat, S.L., and E.I. Thorsos, "Numerical studies of rough surface scattering models," 120th Meeting of the Acoustical Society of America, San Diego, California, Nov. 1990, *J. Acoust. Soc. Am.*, vol. 88, Suppl. 1, S86, Fall 1990. (P)
- [2] Yang, T.Q., and S.L. Broschat, "A numerical comparison of scattering model results for 2-D randomly-rough Dirichlet surfaces," IEEE Antennas and Propagation Society International Symposium and URSI Radio Science Meeting, London, Ontario, Canada, Jun. 1991. (P,D)
- [3] Broschat, S.L., and E.I. Thorsos, "A numerical study of the small slope approximation for rough surface scattering," Topical Meeting of the International Commission for Optics, Atmospheric, Volume, and Surface Scattering and Propagation, Florence, Italy, Aug. 1991. (P,Pr)

- [4] Ivanova, K., and S.L. Broschat, "The local parabolic approximation for rough surface scattering," 123rd Meeting of the Acoustical Society of America, Salt Lake City, Utah, May 1992, *J. Acoust. Soc. Am.*, vol. 91, no. 4, pt. 2, 2341, Apr. 1992. (P)
- [5] Broschat, S.L., and T.Q. Yang, "The small slope approximation for acoustic scattering at a fluid-solid interface," 123rd Meeting of the Acoustical Society of America, Salt Lake City, Utah, May 1992, *J. Acoust. Soc. Am.*, vol. 91, no. 4, pt. 2, 2341, Apr. 1992. (P)
- [6] Schneider, J.B., and S.L. Broschat, "Wave scattering from perfectly conducting rough surfaces using the FDTD method," IEEE Antennas and Propagation Society International Symposium and URSI Radio Science Meeting, Chicago, Illinois, Jul. 1992. (P,D)
- [7] Hastings, F., S.L. Broschat, and J.B. Schneider, "A Monte Carlo FDTD Method for rough surface scattering," IEEE Antennas and Propagation Society International Symposium and URSI Radio Science Meeting, Ann Arbor, Michigan, Jun.-Jul. 1993. (P,D)
- [8] Ivanova, K., S.L. Broschat, and E.I. Thorsos, "The small slope approximation for wave scattering from Neumann surfaces," Progress in Electromagnetics Research Symposium, Pasadena, California, Jul. 1993. (P,Pr)
- [9] Hastings, F.D., S.L. Broschat, and J.B. Schneider, "The FDTD method for scattering from rough surfaces: Oblique incidence," IEEE Antennas and Propagation Society International Symposium and URSI Radio Science Meeting, Seattle, Washington, Jun. 1994. (P,D)
- [10] Schneider, J.B., and S.L. Broschat, "The MEI method applied to random rough surfaces," IEEE Antennas and Propagation Society International Symposium and URSI Radio Science Meeting, Seattle, Washington, Jun. 1994. (P,D)
- [11] Broschat, S.L., and E.I. Thorsos, "The small slope approximation for rough surface scattering," IEEE Antennas and Propagation Society International Symposium and URSI Radio Science Meeting, Seattle, Washington, Jun. 1994. (P,D)
- [12] Schneider, J.B., S.L. Broschat, and P.J. Flynn, "Finite difference simulations of propagation in a shallow water environment," 128th Meeting of the Acoustical Society of America, Austin, Texas, Nov./Dec. 1994, *J. Acoust. Soc. Am.*, vol. 96, no. 5, pt. 2, 3265, Nov. 1994. (P)
- [13] Broschat, S.L., and E.I. Thorsos, "Numerical studies of the small slope approximation for rough surface scattering using a Pierson-Moskowitz spectrum," 129th Meeting of the Acoustical Society of America, Washington, DC, May/June 1995, *J. Acoust. Soc. Am.*, vol. 97, no. 5, pt. 2, 3404, May 1995. (P)
- [14] Broschat, S.L., and E.I. Thorsos, "A preliminary numerical study of the non-local small slope approximation," 132nd Meeting of the Acoustical Society of America, Honolulu, HI, Dec. 1996, *J. Acoust. Soc. Am.*, vol. 100, no. 4, pt. 2, 2702, Oct. 1996. (P)
- [15] Hastings, F.D., J.B. Schneider, and S.L. Broschat, "Scattering from rough pressure-release surfaces using the finite-difference time-domain method," 132nd Meeting of the Acoustical Society of America, Honolulu, HI, Dec. 1996, *J. Acoust. Soc. Am.*, vol. 100, no. 4, 2798, Oct. 1996. (P)
- [16] Hastings, F.D., J.B. Schneider, and S.L. Broschat, "A Monte Carlo FDTD technique for scattering from rough elastic bottoms," 132nd Meeting of the Acoustical Society of America, Honolulu, HI, Dec. 1996, *J. Acoust. Soc. Am.*, vol. 100, no. 4, pt. 2, 2798, Oct. 1996. (P)

[17] Hastings, F.D., J.B. Schneider, S.L. Broschat, and E.I. Thorsos, "Scattering from rough fluid-fluid interfaces using the finite-difference time-domain method," 133rd Meeting of the Acoustical Society of America, State College, PA, Jun. 1997, *J. Acoust. Soc. Am.*, vol. 101, no. 5, pt. 2, 3065, May 1997. (P)

[18] Broschat, S.L., "Coherent reflection loss from a Pierson-Moskowitz sea surface using the NLSSA," 134th Meeting of the Acoustical Society of America, San Diego, CA, Dec. 1997, *J. Acoust. Soc. Am.*, vol. 102, no. 5, pt. 2, 3215, Nov. 1997. (P)

[19] Hastings, F.D., J.B. Schneider, S.L. Broschat, and E.I. Thorsos, "A comparison of the finite-difference time-domain and integral equation methods for scattering from shallow water sediment bottoms," 135th Meeting of the Acoustical Society of America and 16th International Congress on Acoustics, Seattle, WA, Jun. 1998. (P,Pr)

[20] Broschat, S.L., and E.I. Thorsos, "A review of the SSA for rough surface scattering," 135th Meeting of the Acoustical Society of America and 16th International Congress on Acoustics, Seattle, WA, Jun. 1998. (P,Pr)

[21] Thorsos, E.I., and S.L. Broschat, "The lowest-order small slope approximation for rough surface scattering," 135th Meeting of the Acoustical Society of America and 16th International Congress on Acoustics, Seattle, WA, Jun. 1998. (P,Pr)

III. Invited Talks

[1] Broschat, S.L., "The small slope approximation for wave scattering from randomly rough surfaces using a Pierson-Moskowitz spectrum," IEEE IGARSS'94, Cal Tech, Pasadena, California, Aug. 1994. (P,D)

[2] Schneider, J.B., P.J. Flynn, and S.L. Broschat, "Understanding acoustic propagation in shallow water via animations," 131st Meeting of the Acoustical Society of America, Indianapolis, Indiana, May 1996, *J. Acoust. Soc. Am.*, vol. 99, no. 4, pt. 2, 2552, Apr. 1996. (P)

[3] Broschat, S.L., and E.I. Thorsos, "Accuracy of the small slope approximation for a Gaussian spectrum," Progress in Electromagnetics Research Symposium, Innsbruck, Austria, Jul. 1996. (P,Pr)

[4] Broschat, S.L., J.B. Schneider, F.D. Hastings, and P.J. Flynn, "Computational and theoretical models for rough surface and bottom scattering," International Conference on Shallow-Water Acoustics, Beijing, China, Apr. 1997. (P,Pr)

[5] Broschat, S.L., and E.I. Thorsos, "The non-local small slope approximation for rough surface scattering," Progress in Electromagnetics Research Symposium, Cambridge, Massachusetts, Jul. 1997. (P,Pr)

[6] Hastings, F.D., S.L. Broschat, and J.B. Schneider, "A Monte Carlo contour path FDTD method for scattering from randomly rough dielectric surfaces," IEEE Antennas and Propagation Society International Symposium and URSI Radio Science Meeting, Montreal, Canada, Jul. 1997. (P,D)

IV. Artifacts

Videotape of animations of acoustic wave propagation.

V. Journal Publications

- [1] Broschat, S.L., E.I. Thorsos, and A. Ishimaru, "A heuristic algorithm for the bistatic radar cross section for random rough surface scattering," *IEEE Trans. Geosci. Rem. Sens.*, vol. 28, no. 2, 202-206, 1990.
- [2] Yang, T.Q., and S.L. Broschat, "A comparison of scattering model results for two-dimensional randomly-rough surfaces," *IEEE Trans. Antennas Propagat.*, vol. 40, no. 12, 1505-1512, Dec. 1992.
- [3] Broschat, S.L., "The phase perturbation approximation for rough surface scattering from a Pierson-Moskowitz sea surface," *IEEE Trans. Geosci. Rem. Sens.*, vol. 31, no. 1, 278-283, Jan. 1993.
- [4] Broschat, S.L., "The small slope approximation reflection coefficient for scattering from a 'Pierson-Moskowitz' sea surface," *IEEE Trans. Geosci. Rem. Sens.*, vol. 31, no. 5, 1112-1114, Sep. 1993.
- [5] Ivanova, K., and S.L. Broschat, "The method of the local parabolic approximation for rough surface scattering," *J. Acoust. Soc. Am.*, vol. 94, no. 4, 2326-2333, Oct. 1993.
- [6] Yang, T.Q., and S.L. Broschat, "Acoustic scattering from a fluid-elastic solid interface using the small slope approximation," *J. Acoust. Soc. Am.*, vol. 96, no. 3, 1796-1804, Sep. 1994.
- [7] Schneider, J.B., and S.L. Broschat, "The Measured Equation of Invariance method applied to randomly rough surfaces," *Applied Computational Electromagnetics Society Journal*, vol. 10, no. 1, 19-30, Mar. 1995.
- [8] Thorsos, E.I., and S.L. Broschat, "An investigation of the small slope approximation for scattering from rough surfaces: Part I Theory," *J. Acoust. Soc. Am.*, vol. 97, no. 4, 2082-2093, Apr. 1995.
- [9] Hastings, F.D., J.B. Schneider, and S.L. Broschat, "A Monte-Carlo FDTD technique for rough surface scattering," *IEEE Trans. Antennas Propagat.*, vol. 43, no. 11, 1183-1191, Nov. 1995.
- [10] Hastings, F.D., J.B. Schneider, and S.L. Broschat, "Application of the perfectly matched layer (PML) absorbing boundary condition to elastic wave propagation," *J. Acoust. Soc. Am.*, vol. 100, no. 5, 3061-3069, Nov. 1996.
- [11] Broschat, S.L., and E.I. Thorsos, "An investigation of the small slope approximation for scattering from rough surfaces: Part II Numerical studies," *J. Acoust. Soc. Am.*, vol. 101, no. 5, 2615-2625, May 1997.
- [12] Hastings, F.D., J.B. Schneider, and S.L. Broschat, "A finite-difference time-domain solution to scattering from a rough pressure-release surface," *J. Acoust. Soc. Am.*, vol. 102, no. 6, 3394-3400, Dec. 1997.
- [13] Schneider, J.B., C.L. Wagner, and S.L. Broschat, "Implementation of transparent sources embedded in acoustic finite-difference time-domain grids," *J. Acoust. Soc. Am.*, vol. 103, no. 1, 136-142, Jan. 1998.



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July 1, 1998

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Dear Sir or Madam:

Enclosed is the submittal of the final technical report for Dr. Shira Broschat, School of Electrical Engineering and Computer Science, Washington State University, Grant No. N00014-89-J-1989. Also, attached to the report is the completed SF 298.

Please notify the appropriate people that this report and the SF 298 has been received.

If you need further information, please call me at (509) 335-9661 or email me at nshrope@wsu.edu.

Sincerely,

A handwritten signature in cursive script that reads "Nancy Shrope".

Nancy Shrope
Administrative Manager

pc: L. Clausen
E. Harvey