Measurements and Analysis of Reverberation, Target Echo, and Clutter

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LONG-TERM GOALS

The long-term goal of this work is to better understand and model reverberation and clutter in shallow water environments, and to develop techniques for Rapid Environmental Assessment (REA) and environmentally adaptive sonar.

OBJECTIVES

The current project is a joint collaboration between Defence Research & Development Canada Atlantic (DRDC Atlantic) and the Applied Research Laboratory of The Pennsylvania State University (ARL/PSU) to analyze and model reverberation, target echo, and clutter data in shallow water. It allows the PI to spend approximately three months each year at ARL/PSU. The collaboration leverages programs in Canada, US, and a joint research project with the NATO Undersea Research Centre (NURC). The primary effort is analysis and interpretation of data, together with development and validation of improved modeling algorithms. One focus is the performance of directional sensors in towed arrays. The PI participated in the Clutter '07 and BASE '07 Mediterranean sea trials with NURC; another trial is scheduled for 2009. The data from the 2007 and other sea trials are being analyzed. A fast shallow water sonar model that includes target echo and clutter is being developed; it will have bistatic capability and range-dependence. The models are being validated as part of the ONR Reverberation Modeling Workshops.

APPROACH

The PI spends three months per year at ARL/PSU, conducting joint research primarily with Drs. John Preston and Charles Holland. DRDC Atlantic generally funds Dr. Preston for two weeks of research in Canada. Additional collaboration takes place throughout the year. The main objective of this collaboration is to analyze, model, and interpret data received on towed arrays during reverberation and clutter sea trials. The primary outputs of the collaboration are manuscripts for joint publications in refereed journals. Secondary outputs are improved models and algorithms.

Foci of this collaboration are Joint Research Projects (JRPs) between NURC, Canada, and several US research laboratories (ARL in particular). The current JRP is "Characterizing and Reducing Clutter for Broadband Active Sonar". The most recent trials were Clutter '07, which took place on the Malta Plateau in May 2007, and follow-on trial BASE '07 which took place on the Malta Plateau and two other areas south of Sicily. The PI participated in the Clutter trial, and the first part of the BASE trial. Another trial, Clutter '09, is scheduled for May 2009. The current project emphasizes examination and

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14. ABSTRACT
The long-term goal of this work is to better understand and model reverberation and clutter in shallow water environments, and to develop techniques for Rapid Environmental Assessment (REA) and environmentally adaptive sonar.

15. SUBJECT TERMS

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interpretation of data from several towed arrays with directional elements specifically the NURC and ONR cardioid arrays with triplets of omnidirectional elements and the DRDC DASM (Directional Array Sensor Module) array with omnidirectional plus dipole sensors. Models are being extended to compare the performance of these arrays. Data from the Clutter '07 and BASE '07 trials (as well as the earlier Boundary '04 and BASE '04 trials) are being analyzed along the lines of previous experiments [1, 2, 3].

As part of the analysis, a fast shallow-water reverberation model [4, 5] based on normal modes is being extended to a bistatic range-dependent sonar model that includes target echo and feature scattering [6]. Like the reverberation model, it will be computationally-efficient and include the 3-D effects of towed array beam patterns, signal excess, and time-spreading in order to compare with experimental measurements.

The ONR Reverberation Modeling Workshops [7, 8] have been a more recent focus for collaboration. The PI extended and exercised two of his models on a number of problems [5], and collaborated with Preston in developing a Matlab-based model [9]. The model will also be validated against more computationally-intensive physics-based models developed by other researchers. Other collaborations with Holland and Ainslie led to presentations at a Special Session of the Acoustical Society of America in November 2007 [10, 11], and journal publications are in progress [12]. The PI was a member of the problem definition committee for the second Reverberation Modeling Workshop held in May 2008.

WORK COMPLETED

The September 2007 Maritime REA Conference in Lerici, Italy, provided the impetus to complete a pair of journal articles summarizing the reverberation work during the 1996-1998 Rapid Response Exercises and follow-on JRPs with NURC. Results had been presented at various meetings, and short papers at conference proceedings, but not written up in detail. The 2007 Maritime REA Conference provided the opportunity to describe in detail the procedure used to extract environmental information from reverberation data. A poster presentation was prepared for the conference [13], and two papers on the measurement and modeling methodology have been accepted for publication [2, 3].

The PI participated in the Reverberation Modeling Workshops at Austin, TX, in November 2006 and May 2008. The 2006 ONR Reverberation Modeling Workshop provided the stimulus to test the PI's reverberation model in a series of problems. The normal mode models OGOPOGO/NOGRP were applied to a number of problems, NOGRP was extended to handle different types of scattering functions, and a Matlab-based model was developed by Preston using the Ellis [4] normal-mode formulation and the Westwood ORCA model [14, 15]. Results were submitted in March 2007 for publication in the Workshop Proceedings. The Proceedings has been delayed, so the contributions were published as DRDC Technical Memoranda [5, 9]. The normal-mode method compared quite well with other results, and seems to have been used to calibrate a number of others for Problem 11 (isovelocity water, with 3-D Lambert scattering) at/after the 2006 Workshop; after considerable interaction between the organizers and the participants, the updated results at the May 2008 Workshop showed many models now to be in very good agreement [8].

Follow-on work on Workshop Problem 11 has been done with Ainslie and Harrison comparing rays, modes, and energy flux methods. One interesting feature at 250 Hz are the modal effects that appear at several hundred seconds in time. A presentation was made at the November 2007 meeting of the

Acoustical Society of America [11], and a journal paper is in progress.

Another interesting development has been the comparison of predictions for the rough bottom scattering for Problem 5. This is discussed in the “Results” section below.

In 2007, the normal-mode reverberation model was extended to handle scattering from a sub-bottom interface. Collaboration with Charles Holland led to a comparison of the normal-mode and energy flux approaches. Some results were presented at the Special Session on Reverberation Modeling at the November 2007 meeting of the Acoustical Society of America [10], and a paper has been accepted by the Journal of Computational Acoustics [12]. It is interesting that the normal-mode formulation can be applied to the scattering from a sub-bottom interface simply by changing the depth of the scattering interface. The issues of reciprocity are automatically handled by the normal mode formulation. The 1995 JASA paper [4] inadvertently omitted a density factor in the normal mode propagation term [16]. It did not matter when the scattering occurred at the water-bottom interface, but becomes important if the scattering is at a sub-bottom interface.

The volume reverberation and target echo components [17] of the model are being exercised on the 2008 Workshop problems. A unique (and computationally efficient) component of the model is the way it treats time spreading. This is not very noticeable for reverberation, but is important for feature scattering and target echoes.

The equations for the fast reverberation and target echo models have been recently extended to handle bistatic geometry and range dependence [6]. It is a generalization of the energy-flux approach of Harrison [18]. Matlab code has been developed and calculations performed for bistatic geometry; an example is given in the “Results” section below. Range-dependent reverberation and clutter features can be included, but the propagation is to date only range independent. The next step is to incorporate range dependent propagation using adiabatic modes.

A key part of the reverberation models is the capability to efficiently handle towed array beam patterns to compare with data from broadband sources. The details for a uniform bottom have been described in the REA papers [2, 3]. The extension to bistatic range-dependence is formulated in [6]. Only the flat bottom case has been implemented in the recent Matlab model, but the agreement with data measured with the NURC towed array on the Malta Plateau looks very promising — see an example in the “Results” section below. The spreading of the point target echo across the conical towed array beams is also illustrated. Future work will include multiple clutter features, and range-dependent bathymetry.

RESULTS

This section illustrates a few examples from activities during the past year.

Reverberation Modeling Workshop – Rough bottom scattering

An interesting feature was the effectiveness of the Kuperman-Ingenito [19] expression for modal attenuation in dealing with the rough surface.

Problem 5 from the Reverberation Modeling Workshop had a rough bottom with rms height of 0.141 m and correlation length of 10 m. The organizers provided a scattering strength, and reflection losses with and without the coherent forward scattering loss. At 250 Hz the coherent scattering loss is not

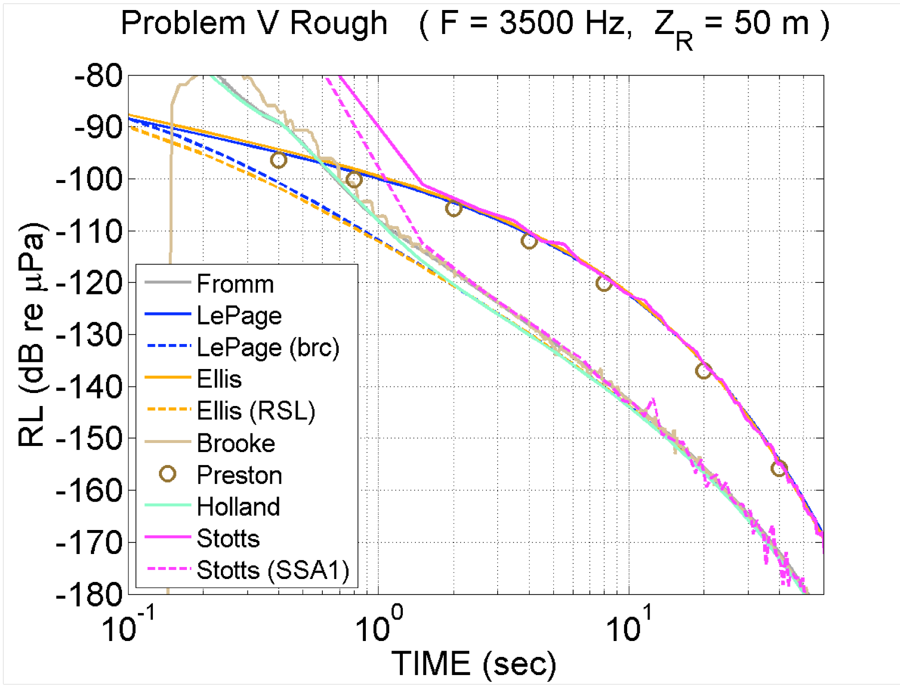


Figure 1. Results from Problem 5 from the Reverberation Modeling Workshop at 3.5 kHz. The upper group of curves use a smooth bottom for propagation, while the lower group include the forward scattering loss. (Figure courtesy of Eric Thorsos [8].)

important, but at 3500 Hz the predictions break into two groups as illustrated in Figure 1 [8]. The upper group has only the smooth-bottom loss, while the lower group includes the coherent loss from the rough bottom.

It was easy to extend the PI's NOGRP reverberation model to handle the backscattering, but the underlying PROLOS normal-mode propagation model [16] did not have a way of incorporating the reflection loss. However, PROLOS did include the Kuperman-Ingenito modal attenuation formula for coherent forward scattering loss [19], which uses the bottom rms roughness only. The reverberation calculated with and without the rough surface loss [5] – "Ellis" and "Ellis (RSL)" in Figure 1 – agrees well with the other calculations.

The agreement was surprising since this option in PROLOS had rarely been used and never validated since the code was developed over 25 years ago. Nor was it expected to work at such high frequencies. Thorsos notes that the Kuperman-Ingenito formula must be a better approximation than the Kirchhoff approximation that they mention in their paper.

Bistatic calculation of reverberation, target echo and signal excess.

The new bistatic reverberation model [6] was applied a problem similar to that of Harrison [20]. Figure 2 illustrates bistatic results with ideal "wedge" beam patterns of width $\Delta\phi = \pi/50$ radians $(3.6°)$. The environment is the 3-D isovelocity case from the ONR Reverberation Modeling Workshop [8]: 100 m of 1500 m/s water over a sand bottom halfspace, with -27 dB Lambert scattering. The source is at 30 m depth and receiver at 50 m, separated in range by 15 km. The source has an intensity of 10 dB for a

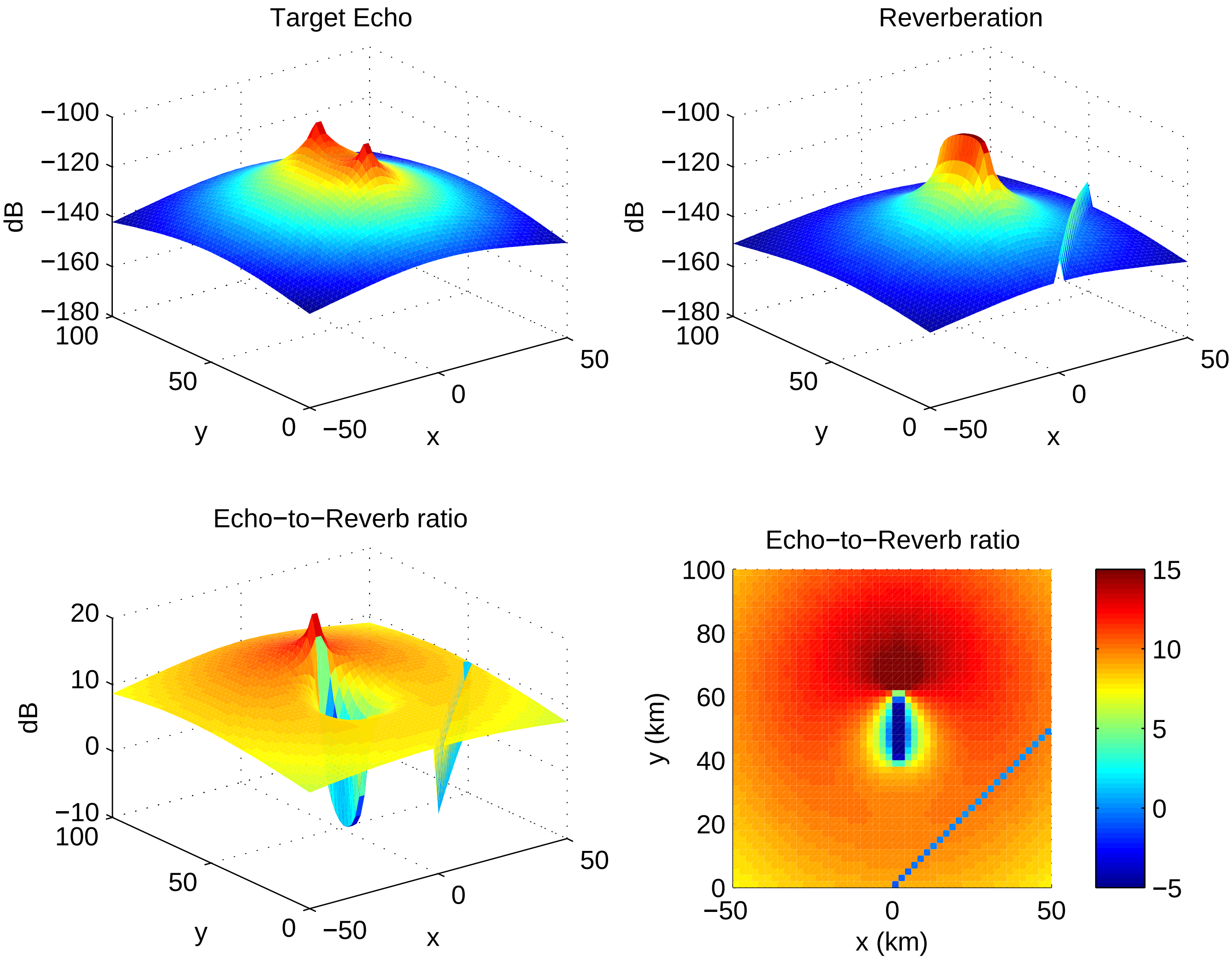


Figure 2. Reverberation, target echo, signal excess (as surface plot and as contour plot) in an isovelocity environment. The diagonal line from (0,0) to (50,50) illustrates 10 dB enhanced scattering.

duration of 0.1 s; the target is at 10 m depth with an echo strength of 10 dB. The calculations were done at 250 Hz, but aside from volume absorption in the water, the reverberation is almost independent of depth and frequency [5]. After the initial bistatic effects, the signal excess becomes more or less independent of range.

It is easy to incorporate spatial dependence in the scattering or echo; the diagonal line from (0,0) to (50,50) in Figure 2 illustrates a 10 dB enhancement in the bottom scattering strength. In the current formulation of the model it is possible to include a different scattering strength at each range point, and/or a different echo strength at each point. The underlying normal-mode propagation model can handle an arbitrary sound speed and bottom profile. The equations have been formulated [6] for range-dependence using adiabatic modes, but the Matlab code has not yet been completed.

Towed array reverberation and clutter feature

An important feature of the reverberation models has been the ability to handle realistic arrays for comparison with data. An example using the new Matlab reverberation/echo model [6] is shown here. Figure 3 illustrates data [21] from the Malta Plateau received on the NATO Undersea Research Centre (NURC) towed array on a heading of 176°. The array has 85 beams, with Hann weights, equally spaced in cosine of the steering angle, and mapped into azimuth. Note that the echoes from the Campo Vega oil rig and tender (red diamonds) near N 36.54° E 14.66° are spread over several beams near aft endfire; at frequencies below 1750 Hz the echoes would be spread over even more beams. The data from the linear array has been used, so the towed array data shows left-right ambiguity about the array heading. Additional clutter features are shown as black squares on the upper plot. The source (189 dB energy flux density spectrum level) is at 90 m and receiver at 70 m. The model predictions, with bottom parameters from the 630 Hz "manual fit" from Ref. [21], are shown in the lower plot. They illustrate the towed array effects, including the "X" pattern of reverberation at short ranges, and the beam spreading of the Campo Vega echo. The target has been modeled with a 30 dB echo strength at a single azimuth. The echo was calculated for 7 beams (vertical slices through 7 different conical towed array beampatterns, but with the target at the same azimuth). The "X" pattern of the reverberation is due to the next-to-endfire conical beam pattern, which is fairly broad and picks up reverberation around 13° grazing angle from the aft endfire direction as well the reverberation from the mapped azimuth. In the upper figure the data at longer ranges and several beams from endfire shows higher ambient noise from the Campo Vega oil rig and tender.

Only one target feature is included in the model prediction, and an overall noise level of 35 dB has been assumed on all beams. It is easy to include additional clutter features, and a different noise level on each beam.

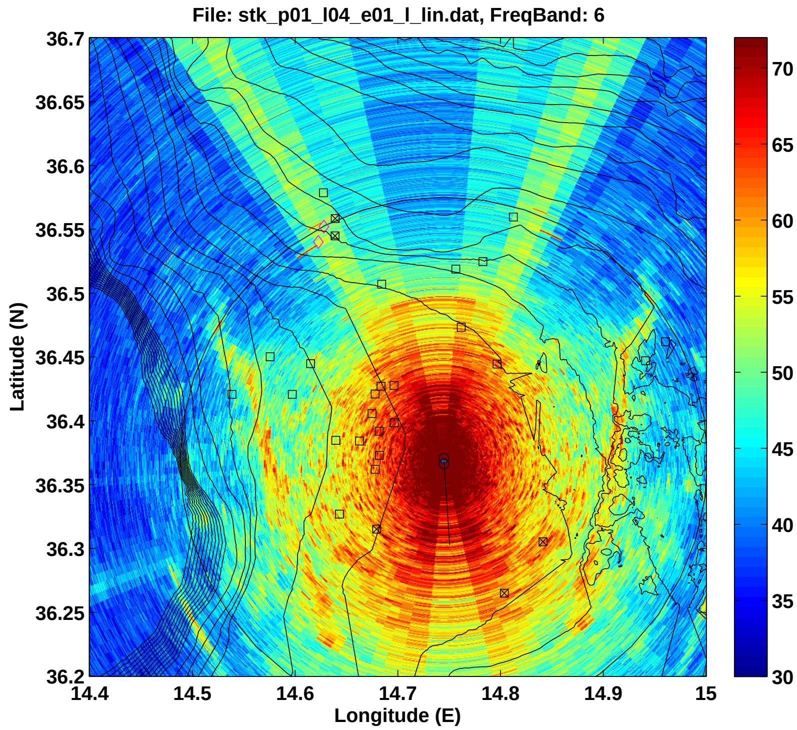
The geometry in this example was range independent and essentially monostatic, so effective beam patterns [22] for each beam were used in the reverberation calculations. In bistatic geometry, or range-dependent environments, the azimuthal integration would have to be performed at each range instead of being pre-computed.

IMPACT/APPLICATIONS

From an operational perspective, clutter is viewed as one of the most important problems facing active sonar in shallow water. The long-term objective of this work is to better understand and model reverberation and clutter in shallow water environments, and to develop techniques for Rapid Environmental Assessment (REA) [23, 24] and environmentally adaptive sonar. Parts of the research have been spun off into a DRDC TIAPS (Towed Integrated Active-Passive Sonar) Technology Demonstrator which has been evaluated in ASW exercises against submarine targets. The work on clutter is related to the DRDC effort in auralization and co-operative work with TTCP and other ONR efforts.

If the target echo model can be validated, this could be a useful method for estimating the target strength of clutter features—and even submarines—in multipath shallow water environments.

One goal is to be able to use the model with real clutter data from a towed array. One could subtract out the background reverberation, including range-dependent effects and known scattering features, leaving



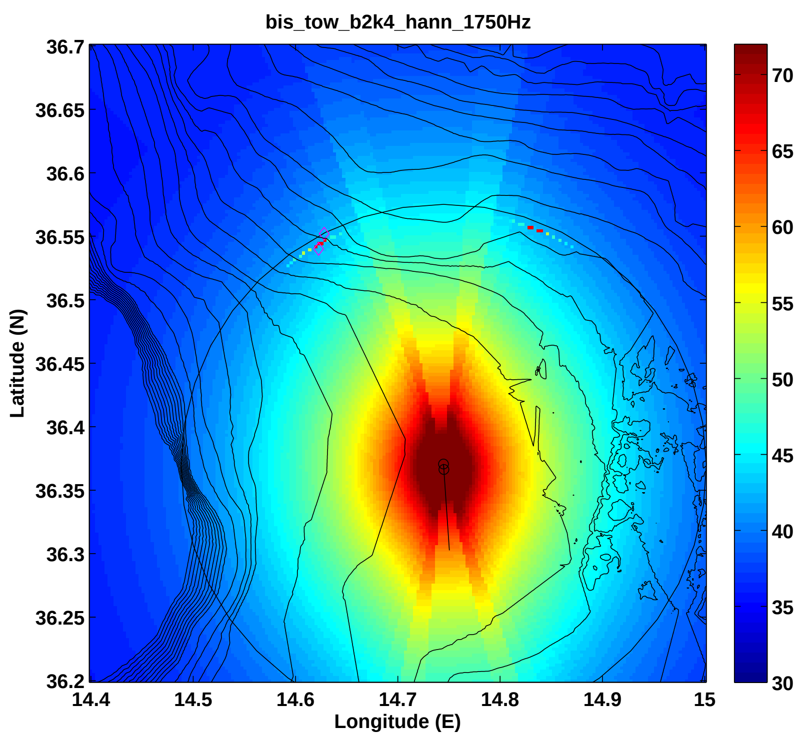


Figure 3. Monostatic towed array data from the Malta plateau (upper figure) at 1750 Hz where the beams have the best resolution, and model prediction (lower figure). The figures illustrate the towed array effects, including the "X" pattern of reverberation at short ranges, and the beam spreading of point target at Campo Vega.

behind the unidentified clutter on a display. These unidentified features would then be investigated by other techniques to try to determine their nature.

RELATED PROJECTS

This project contributes to the US/Canada/NURC Joint Research Project "Characterizing and Reducing Clutter in Broadband Active Sonar" which receives substantial funding from ONR. This ONR project also contributes to the DRDC Atlantic research program:
http://www.atlantic.drdc-rddc.gc.ca/researchtech/researchareas_e.shtml,
in particular, Underwater Sensing and Countermeasures,
http://www.atlantic.drdc-rddc.gc.ca/researchtech/underwater-intro_e.shtml.

As well, the personal interaction on this project facilitates additional collaborations between scientists in the various research laboratories.

REFERENCES

[1] D. D. Ellis, J. R. Preston, R. Hollett, and J. Sellschopp. Analysis of towed array reverberation data from 160 to 4000 Hz during Rapid Response 97. SACLANTCEN Report SR-280, SACLANT Undersea Research Centre, La Spezia, Italy, July 2000. 58 pp.

[2] John R. Preston and Dale D. Ellis. Extracting bottom information from towed array reverberation data. Part I: Measurement methodology. *J. Marine Systems*, 2008. Accepted for publication.

[3] Dale D. Ellis and John R. Preston. Extracting bottom information from towed array reverberation data. Part II: Extraction procedure and modelling methodology. *J. Marine Systems*, 2008. Accepted for publication.

[4] Dale D. Ellis. A shallow-water normal-mode reverberation model. *J. Acoust. Soc. Am.*, 97:2804–2814, 1995.

[5] Dale D. Ellis. Normal-mode models OGOPOGO and NOGRP applied to the 2006 ONR Reverberation Modeling Workshop problems. TM 2006-289, DRDC Atlantic, Dartmouth, NS, Canada, June 2008.

[6] Dale D. Ellis, John R. Preston, Paul C. Hines, and Victor Young. Bistatic signal excess calculations over variable bottom topography using adiabatic normal modes. In Peter L. Nielsen, Chris H. Harrison, and Jean-Claude Le Gac, editors, *International Symposium on Underwater Reverberation and Clutter*, pages 97–104. NATO Undersea Research Centre, La Spezia, Italy, 2008. Conference held at Lerici, Italy, 9–12 September 2008. Invited paper presented by D. D. Ellis, 18 slides.

[7] John S. Perkins and Eric I. Thorsos. Overview of the reverberation modeling workshops. *J. Acoust. Soc. Am.*, 122:3074, 2007. Abstract 4aUW1. Special session on "Underwater Reverberation Measurements and Modeling", 154th Meeting of Acoustical Society of America, 27 Nov – 1 Dec 2007, New Orleans, LA, USA.

[8] Eric I. Thorsos and John S. Perkins. Overview of the reverberation modeling workshops. In Peter L. Nielsen, Chris H. Harrison, and Jean-Claude Le Gac, editors, *International Symposium on*

Underwater Reverberation and Clutter, pages 3–14. NATO Undersea Research Centre, La Spezia, Italy, 2008. Conference held at Villa Marigola, Lerici, Italy, 9–12 September 2008.

[9] John R. Preston and Dale D. Ellis. Report on a normal mode and Matlab based reverberation model. DRDC Atlantic TM 2006-290, DRDC Atlantic, Dartmouth, NS, Canada, June 2008.

[10] Dale D. Ellis and Charles W. Holland. A comparison of two modeling approaches for reverberation in a shallow-water waveguide where the scattering arises from a sub-bottom interface. *J. Acoust. Soc. Am.*, 122:3091, 2007. Abstract 4pUW4. Special session on "Underwater Reverberation Measurements and Modeling", 154th Meeting of Acoustical Society of America, 27 Nov – 1 Dec 2007, New Orleans, LA, USA.

[11] Dale D. Ellis, M. A. Ainslie, and C. H. Harrison. A comparison of ray, normal-mode, and energy flux results for reverberation in a Pekeris waveguide. *J. Acoust. Soc. Am.*, 122:3075, 2007. Abstract 4aUW9. Special session on "Underwater Reverberation Measurements and Modeling", 154th Meeting of Acoustical Society of America, 27 Nov – 1 Dec 2007, New Orleans, LA, USA.

[12] Charles W. Holland and Dale D. Ellis. A comparison of two modeling approaches for reverberation in a shallow-water waveguide where the scattering arises from a sub-bottom interface. *J. Comp. Acoust.*, 2008. Accepted 2007.

[13] Dale D. Ellis and John R. Preston. Extracting bottom information from towed-array data. In *Rapid Environmental Assessment (REA) Conference*, 2007. Poster at Conference held in Lerici, Italy, 25-27 September 2007.

[14] E. K. Westwood, C. T. Tindle, and N. R. Chapman. A normal mode model for acousto-elastic ocean environments. *J. Acoust. Soc. Am.*, 100:3631–3645, 1996.

[15] E. K. Westwood. ORCA Version 2.0 Users Guide. Technical report, ARL-UT, 1998.

[16] Dale D. Ellis. A two-ended shooting technique for calculating normal modes in underwater sound propagation. DREA Report 85/105, Defence Research Establishment Atlantic, Dartmouth, NS, Canada, September 1985.

[17] Dale D. Ellis, Terry J. Deveau, and James A. Theriault. Volume reverberation and target echo calculations using normal modes. In *Oceans '97 MTS/IEEE Conference Proceedings*, volume 1, pages 608–611. IEEE, Piscataway, NY, USA, Oct. 1997.

[18] Chris H. Harrison. Fast bistatic signal-to-reverberation-ratio calculation. *J. Comp. Acoust.*, 13:317–340, 2005.

[19] W. A. Kuperman and F. Ingenito. Attenuation of the coherent component of sound propagation in shallow water with rough boundaries. *J. Acoust. Soc. Am.*, 61:1178–1187, 1977.

[20] C. H. Harrison. Bistatic reverberation and signal excess solutions in closed-form. *J. Acoust. Soc. Am.*, 2004. submitted.

[21] John R. Preston. Using cardioid arrays for reverberation analysis and inversions. *IEEE J. Oceanic Eng.*, 32(4):879–896, 2007.

[22] Dale D. Ellis. Effective vertical beam patterns for ocean acoustic reverberation calculations. *IEEE J. Oceanic Eng.*, 16:208–211, 1991.

[23] J. Sellschopp. Rapid environmental assessment for naval operations. SACLANTCEN Report SR-328, SACLANT Undersea Research Centre, La Spezia, Italy, May 2000.

[24] Brian G. Whitehouse, Paul Hines, Dale Ellis, and Charlie N. Barron. Rapid Environmental Assessment within NATO. *Sea Technology*, 45(11):10–14, 2004.

PUBLICATIONS

The following publications were accepted or published during the past year:

- John R. Preston and Dale D. Ellis. Extracting bottom information from towed array reverberation data. Part I: Measurement methodology. *J. Marine Systems*, 2008. [in press, refereed]
- Dale D. Ellis and John R. Preston. Extracting bottom information from towed array reverberation data. Part II: Extraction procedure and modelling methodology. *J. Marine Systems*, 2008. [in press, refereed]
- Charles W. Holland and Dale D. Ellis. A comparison of two modeling approaches for reverberation in a shallow-water waveguide where the scattering arises from a sub-bottom interface. *J. Comp. Acoust.*, 2008. [in press, refereed]
- Dale D. Ellis, John R. Preston, Paul C. Hines, and Victor Young. Bistatic signal excess calculations over variable bottom topography using adiabatic normal modes. In Peter L. Nielsen, Chris H. Harrison, and Jean-Claude Le Gac, editors, *International Symposium on Underwater Reverberation and Clutter*, pages 97–104. NATO Undersea Research Centre, La Spezia, Italy, 2008. [published]
- Dale D. Ellis. Normal-mode models OGOPOGO and NOGRP applied to the 2006 ONR Reverberation Modeling Workshop problems. TM 2006-289, DRDC Atlantic, Dartmouth, NS, Canada, June 2008. [published]
- John R. Preston and Dale D. Ellis. Report on a normal mode and Matlab based reverberation model. DRDC Atlantic TM 2006-290, DRDC Atlantic, Dartmouth, NS, Canada, June 2008. [published]