

Modeling and Analysis of Target Echo and Clutter in Range-Dependent Bistatic Environments: FY12 Annual Report for ONR

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Award Number: N00014-11-1-0476
<http://www.onr.navy.mil/en/Science-Technology/Departments/Code-32.aspx>

LONG-TERM GOALS

The long-term goal of this work is to better understand and model reverberation, target echo, 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 Principal Investigator (PI) to spend approximately two months each year at ARL/PSU. The collaboration leverages programs in Canada and the US, and joint research projects with the NATO Centre for Maritime Research and Experimentation (CMRE) [formerly known as NATO Undersea Research Centre (NURC)]. The primary effort is analysis and interpretation of data, together with development and validation of improved modeling algorithms.

APPROACH

The PI spends two months per year at ARL/PSU, conducting joint research primarily with Dr. John Preston and Dr. Charles Holland. 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 conference proceedings and refereed journals. Secondary outputs are improved models and algorithms.

Foci of this collaboration have been Joint Research Projects (JRPs) between CMRE, Canada and several US research laboratories (ARL in particular). The JRP “Characterizing and Reducing Clutter for Broadband Active Sonar” is now complete. A proposed JRP “Modeling and Stimulation for ASW Active Sonar Trainers” for years 2011–2013 was accepted by CMRE, but no resources seem to have been yet allocated. The focus for experiment design and data analysis is now the ONR mid-frequency

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 2012		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE Modeling and Analysis of Target Echo and Clutter in Range-Dependent Bistatic Environments: FY12 Annual Report for ONR				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) DRDC Atlantic P. O. Box 1012, Dartmouth, NS, Canada B27 3Z7				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES The original document contains color images.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 12	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

reverberation and target echo experiments in the Gulf of Mexico near Panama City, Florida [TH12].

Model development to support experiment design and data interpretation is a major focus of the work. Recent work by the PI has focused on bistatic range-dependent reverberation modeling and target echo calculations. A bistatic range-dependent “Clutter Model” [EP11, EPB12] based on adiabatic normal modes has been developed, and comparisons made with towed array data from the Malta Plateau. The model was recently extended to handle towed arrays with triplet elements, and predictions of reverberation and target echo made [EPB12] in support of the GulfEx12 and TREX13 experiments. Reverberation data from the Malta Plateau have indicated that sub-bottom scattering is important [Hol02], so, in collaboration with Holland, the mode model was initially extended to handle sub-bottom scattering [HE09], and later extended to include sub-bottom range-dependence [HE12].

Over the past few years, the ONR Reverberation Modeling Workshops [PT07, TP08, PT09] have been a focus for collaboration. The PI extended and exercised two of his models on a number of problems [Ell08], and collaborated with Preston in developing a Matlab-based model [PE08]. For the Pekeris model with Lambert bottom scattering, extensive comparisons have been made [AEH11] between energy-flux, normal mode, ray-based models, and analytical approaches, and a journal paper has been submitted [AEH13].

The ONR Reverberation Modeling Workshops (RMW) have stimulated further work; e.g., the 2010 Symposium on Validation of Sonar Performance Assessment Tools [Ain10], sponsored by the UK Institute of Acoustics. The “Weston Symposium” extended [ZAS10] the ONR problems to the full sonar scenario, including matched filter processing, background noise, and signal-to-noise ratio. The PI was a member of the problem definition committee for the second Reverberation Modeling Workshop, held in May 2008, and provided advice on several iterations of the Weston Symposium problem definitions. In addition, structured sessions have been organized at the 2011 Underwater Acoustics Measurements Conference (UAM) and the 2012 European Conference on Underwater Acoustics (ECUA). A similar session at the 2013 ECUA is planned.

WORK COMPLETED

This section summarizes some of the work completed in FY2012.

Analysis of reverberation data from the Malta Plateau has indicated that sub-bottom scattering is important. In 2007–08 the normal model was extended to handle sub-bottom scattering [HE09]. In 2010–2011 it was further extended to handle a range-dependent sub-bottom reverberation. In collaboration with Holland it was shown that slowly-varying sub-bottom features could result in discrete target-like returns. A presentation [HE11] was made at the Fall 2011 meeting of the Acoustical Society of America, and a paper submitted, accepted, and published [HE12]. Some details are given in the “Results” section below.

In 2012, the Clutter Model [EP10, EP11] development was extended to handle left-right ambiguity of the Five Octave Research Array (FORA) triplet array, and preliminary calculations made for the 2013 TREX experiment [EPB12]. Some details are given in the “Results” section below. Comparisons with data from the Malta Plateau were extended to 1750 Hz. In addition, DRDC funded Brooke Numerical Services to enhance the Java GUI interface for a more user-friendly tool [HBTT12].

Additional work was done on the validation of reverberation and target echo models. The comparisons

[AEH11] for the Pekeris model benchmarks were reworked and submitted to the Journal of Computational Acoustics [AEH13]. The details of the near-range fathometer returns, calculated using a ray-path model, were described in a laboratory report [Ell12]. The initial work [Ell11, PE11] on range-dependent RMW and Weston Symposium test cases was extended using the author's model r2d3 [EP12], and Preston's Matlab-ORCA version [PE12]. Additional model-model comparisons were made in collaboration with Ainslie et al. [AZE12].

The PI was co-organizer of a Structured Session on Sonar Performance Modelling and Validation at the 2012 ECUA, and contributed four papers [EP12, EPB12, AZE12, PE12] of which he was principal author of two. A similar Structured Session is planned for the joint UAM/ECUA meeting in 2013.

RESULTS

This section illustrates a few results from the activities mentioned in the previous section. The first example is taken from the 2012 paper at the European Conference on Underwater Acoustics [EPB12]. The second example expands on some material in the journal paper by Holland and Ellis [HE12] on clutter due to non-discrete changes in the environment.

Calculations for GulfEx12 and TREX13 experiments

Reverberation and target echo experiments [TH12] are to be conducted off Panama City, Florida, USA, in 2012 (GulfEx12) and 2013 (TREX13). The receiver is the FORA array [BP03], maintained for ONR by ARL/PSU. It has a triplet section that can be used to form broadside cardioids [Pre07].

For the experiments, the triplet section is to be deployed as a fixed receiver. The 78 elements at 0.2 m spacing (design frequency of 3750 Hz) are Hann-weighted and used to form 79 beams, equally spaced in the sine of the beam steering angle, from forward to aft end fire on each side; the triplets in each element are used to form broadside cardioids on the appropriate side, giving a total of 158 beams.

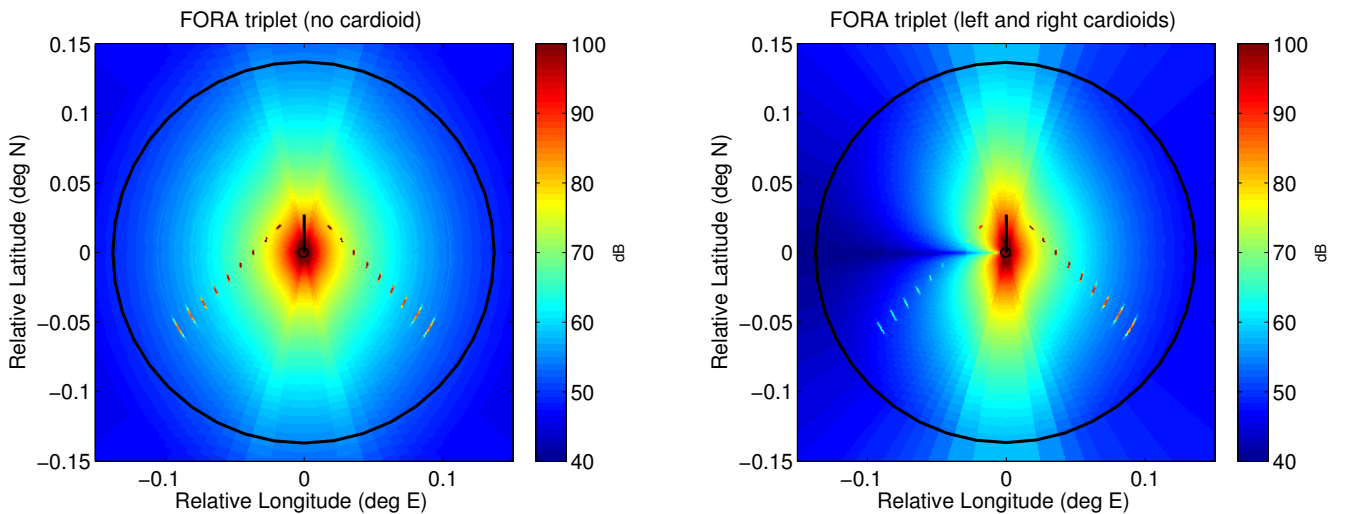


Figure 1: Left: Polar plot of reverberation received on linear array (triplet array without cardioid processing). The black circle indicates 20 s and the black line indicates array heading. Right: Polar plot of target echos and reverberation from right side of array received on triplet array (both left and right beams with cardioid processing).

Calculations were made using the Clutter Model [EP10, EP11, EPB12]. The initial calculations were with the forward end fire beam pointing north, in water of 20 m depth, over a flat, uniform, sandy bottom. The water was assumed isovelocity, 1520 m/s. The bottom properties [HOSH10], from previous experiments in the area, use a half-space with sound speed 1680 m/s, density 2040 kg/m³, and attenuation 0.84 dB/wavelength (or 0.5 dB/m-kHz). Reverberation was assumed due to bottom scattering using Lambert's rule with a -27 dB scattering strength. The source was omnidirectional, operating at 3000 Hz with a source level of 200 dB re 1 μ Pa at 1 m for a duration of 0.1 s. Nine targets (point targets of 15 dB strength) were located in a line eastward of the array at locations $x = [2 : 1 : 10]$ and $y = [2 : -1 : -6]$ km. The ambient noise on each beam was assumed to be 40 dB re 1 μ Pa²/Hz. (For the calculations here, the reverberation exceeds this value). Predictions of the beam time-series to 25 s were calculated, with the source near the midpoint of the array. The source was assumed to be at a depth of 10 m, the array at a depth of 15 m, and the targets at a depth of 10 m.

Figure 1 (left panel) shows reverberation and echo predictions for FORA processed as a linear array; i.e., with the cardioid turned off. The beam time series are displayed on a polar grid, as described in [EP09]; essentially, the beams are mapped into azimuth, and the time mapped into range. In the plots here, the 20 s point is marked by a black circle, and the beam time series are displayed as constant beyond 25 s. The targets appear on both the left-looking and right-looking beams. The right panel simulates the effect of the triplet array, with predictions for the full 360° set of beams, but assuming the reverberation is only coming from area to the right of the array. It illustrates the effect of the cardioid in suppressing signals from the ambiguous beams.

To make the predictions more realistic, bathymetry was included in the calculations. Bathymetry was taken from GEBCO_08 [GEB10], which has a grid spacing of one-half minute in latitude and longitude (about 0.926 km north-south or at the equator). The left panel of Fig. 2 shows the bathymetry in the region of the experiment, with contours at 10 m intervals calculated using Matlab. To ensure that there were modes at each grid point, the minimum water depth (including land areas) was set at 5 m. For clutter objects there were 4 targets on broadside at 1, 2, 5 and 10 km (modeled as 10 dB point objects at 10 m depth), and 9 targets on a SE line at 1 km spacing in both x and y ; i.e., $x = [1 : 1 : 9]$ km, $y = [1 : -1 : -7]$ km; the target strengths were 15 dB with depths selected to alternate between 1 and 10 m. (The 1 m depth was chosen to get some idea of the effect of echos from the hull of a ship). Figure 2 (right) shows a polar plot of the predicted beam time series. Most of the target echoes are visible on the right-looking beams. On the left-looking beams, the echos from the targets at broadside are completely eliminated by the null on the back side of the cardioid; a couple of the echos from the long-range targets have leaked through to the ambiguous beam and are faintly visible.

The line plot in Fig. 3 shows the time series for beam 50 (looking SE at the targets). All echos appear well above the reverberation level. At the longest range 12.7 km (16.7 s) the echo level of the target at 1.0 m depth is about 10 dB lower than for the target at 10.0 m depth.

Target-like clutter due to a slowly-varying environment

It is well understood that discrete objects can lead to clutter. A somewhat counter-intuitive result is shown: that discrete target-like returns can occur from slowly varying seabed structures. The range dependence of the seabed can be weak and smooth – due to changes in layer thicknesses, sound speed, or both. Several examples were given in a journal paper by Holland and Ellis [HE12], mostly using the energy-flux formulation. The phenomenon can be understood using normal modes. Some additional details are presented here.

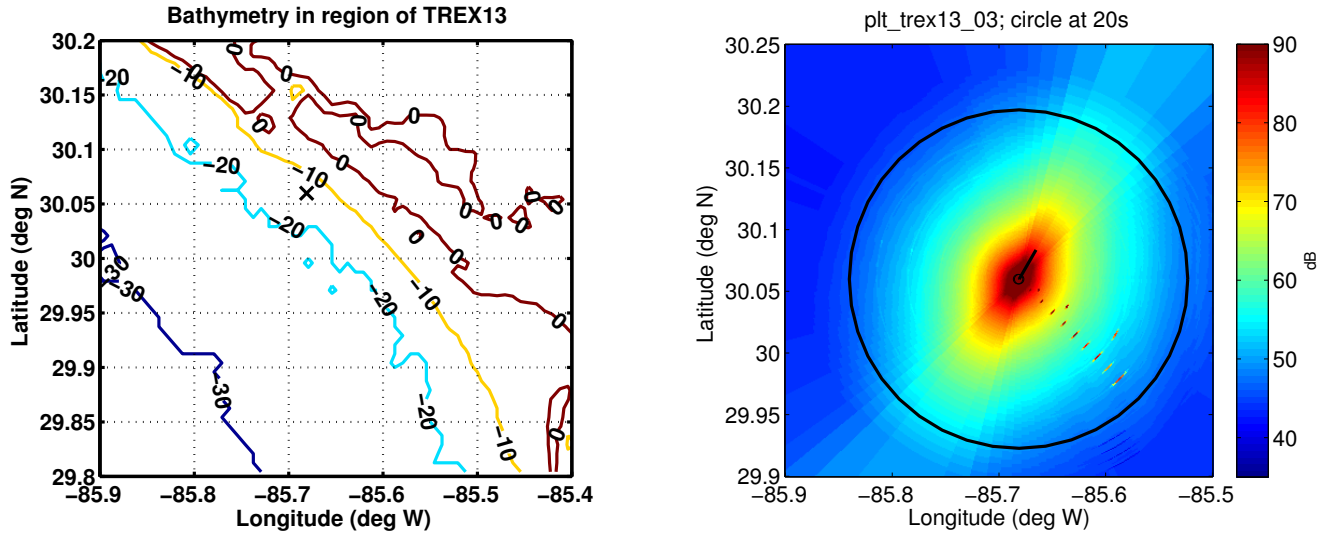


Figure 2: Left: Bathymetry (contours at 0, 10, 20 and 30 m, with depth increasing to the SW) in the region of Panama City. The array location near the centre is marked by $\times$. Right: Polar plot of reverberation and target echos using range-dependent bathymetry and cardioid beamforming. Most of the target echos are visible on the right-looking beams. On the left-looking beams, the echos from the targets at broadside are completely eliminated by the null on the back side of the cardioid; a couple of the echos from the long-range targets have leaked through to the ambiguous beam and are faintly visible.

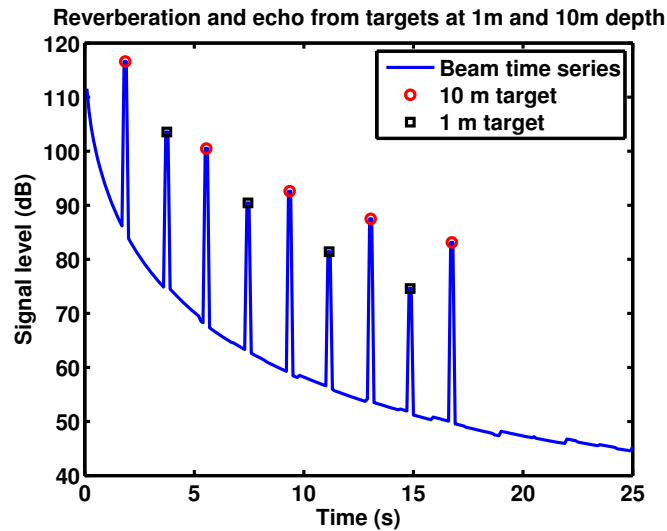


Figure 3: Signal level for towed array beam looking in direction of the targets (at 1 and 10 m depths, alternating).

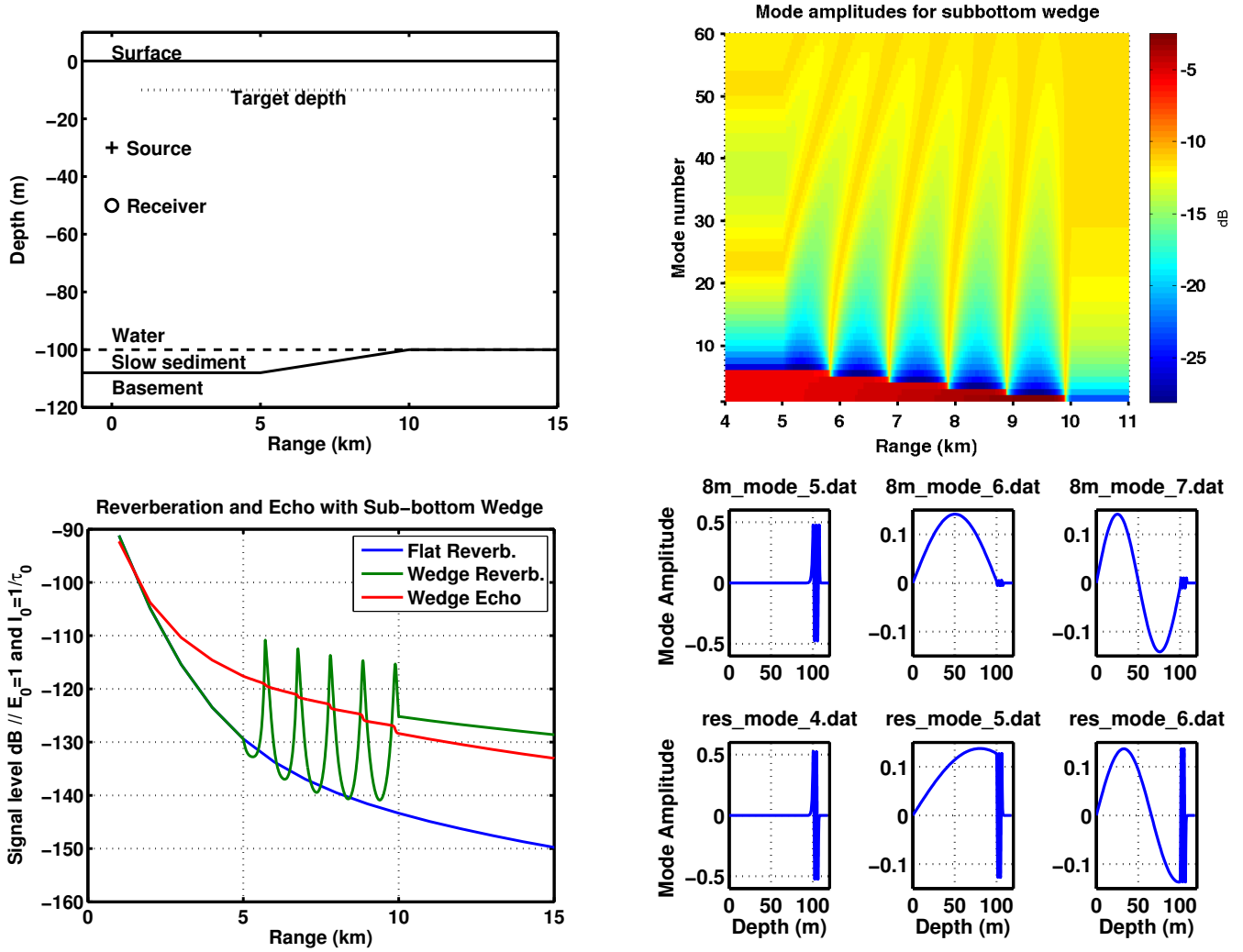


Figure 4: Upper left: The environment with a thin, slow-speed, sub-bottom wedge between 5 and 10 km; Upper right: Mode amplitudes (in dB) in the sub-bottom wedge; Lower left: Reverberation and echo calculations; note the sharp target-like peaks in the reverberation for the wedge case, compared to the flat-bottom case; Lower right: Mode functions (5, 6, 7) for non-resonant (8 m thick layer) and modes 4, 5, and 6 for resonant (6.74 m thick layer) situations.

Figure 4 illustrates some calculations using adiabatic normal modes. The upper left panel shows the environment with a slow-speed sub-bottom wedge, decreasing in depth from 8 m to 0 m between 5 and 10 km. The water sound speed is 1512 m/s, the basement sound speed is 1660 m/s, and the slow sediment layer has a sound speed of 1470 m/s. The scattering occurs at the basement interface. The lower left panel shows the reverberation and target echo as a function of time at 2 kHz, as calculated by the adiabatic normal mode model. This is quite similar to the energy-flux calculations given in the journal paper [HE12]. Note the 5 sharp reverberation peaks, which are due to a resonant effect whereby the energy in the water is transmitted into the soft bottom layer striking the basement interface. The upper right panel shows the mode amplitudes in the sediment as a function of range at 2 kHz. Initially there are 5 modes trapped in the 8 m of sediment. They have high amplitude relative to the waterborne modes, since all the energy is trapped in the layer, rather than spread out over the entire water column. As the sediment thickness decreases with range, they disappear one by one. It is tempting to think of these high-amplitude sediment modes being cut off, spilling their energy into the water column, and sending high intensity reverberation back to the receiver. However, this is not the case, since these modes are not excited by the source in the water column. Rather, the same conditions that give rise to the cutoff of each sediment mode allow energy from the water column to be readily transmitted into the sediment, and back into the water column after scattering from the sediment-basement interface.

The lower right panel compares modes in the non-resonant (8 m layer thickness) and resonant conditions (6.74 m layer thickness). For the non-resonant condition the phase of the sinusoidal mode function in the water is approximately a multiple of π , while for the resonant condition the phase is approximately an odd multiple of $\pi/2$. Note the higher amplitude for the layer modes on the left $\sim \sqrt{2/D}$, where D is the layer thickness, compared to the water-borne modes with amplitude $\sim \sqrt{2/H}$, where H is the water depth. This condition persists to high mode numbers, where even around mode 20 the bottom amplitude is relatively strong. Notice also the strong almost-vertical bands in Fig. 4 (upper right). Recall [Ell95] that the mode amplitude for the scattering is the peak amplitude of the sinusoid, not the actual value of the mode function at the interface since it includes the phase.

The effects of a low-speed resonant layer have been noticed before in regard to propagation. Hastrup [Has80] pointed out that the nulls in the reflection correspond to the condition of trapped modes in the low velocity layer and predicted that these nulls might be seen experimentally as high transmission loss at the null condition. Rubano [Rub80] was the first to see the effect experimentally, and it was later re-examined by Siderius and Hermand [SH99]. In the lower right we see that the target echo has small but abrupt changes in the regions of the high scattering, due to the high losses near these regions.

Normally one would associate high transmission loss with low reverberation. Here it is interesting that, although the high loss is present at only the range of interest, the scattering is also enhanced, so the reverberation exhibits a clutter-like peak.

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) and environmentally adaptive sonar. The work on clutter is related to the DRDC effort in auralization and co-operative work with TTCP and other ONR efforts.

One goal is to be able to use the model with real clutter data from a towed array. 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 could subtract out the background reverberation, including range-dependent effects and known scattering features, leaving behind the unidentified clutter on a display. These unidentified features would then be investigated by other techniques to try to determine their nature.

The sub-bottom clutter mechanism may be a viable hypothesis for areas in which seabed clutter has been observed, but no discrete features, buried or proud, could be found. By using a broadband source, the time-frequency evolution of this clutter could be a useful way to discriminate against other kinds of clutter; e.g., that are due to discrete objects.

TRANSITIONS

Small research contracts for the Clutter Model implementation were let in 2009, 2010, 2011, and 2012. A standalone version with public domain databases and a Java GUI was developed by Brooke Numerical Systems [BKTE10] in 2010. It has been improved in 2012 [HBTT12], and the hope is to be able to fully integrate the Clutter Model for comparison with towed array data.

The newly approved DRDC Technical Demonstration Project AMASE (Advancing Multistatic Active Sonar Employment) will make use of many of the techniques developed under this collaborative project.

The 2010 David Weston Sonar Performance Assessment Symposium held in Cambridge, UK, had number of scenarios based on the ONR Reverberation Modeling Workshop problems, extended to the complete sonar problem. The driving force behind the sonar modeling is the Low Frequency Active Sonar program of TNO and the Royal Netherlands Navy.

RELATED PROJECTS

In the past this project has contributed to the US/Canada/NURC Joint Research Project “Characterizing and Reducing Clutter in Broadband Active Sonar” which received substantial funding from ONR. A new proposal “Modeling and Stimulation for ASW Active Sonar Trainers” has been approved for the 2011–2013 Scientific Program of Work at CMRE, but there has been no activity on it.

Work is being done in preparation for the Panama City reverberation experiments [TH12]; DRDC Atlantic is planning to participate, along with their research vessel CFAV Quest.

This ONR project also contributes to the DRDC Atlantic research program:

[http://www.drdc-rddc.gc.ca/drdc/en/centres/drdc-atlantic-rddc-atlantique/ ...](http://www.drdc-rddc.gc.ca/drdc/en/centres/drdc-atlantic-rddc-atlantique/...)
research-technology-recherche-technologie/

in particular, Underwater Sensing,

[http://www.drdc-rddc.gc.ca/drdc/en/centres/drdc-atlantic-rddc-atlantique/ ...](http://www.drdc-rddc.gc.ca/drdc/en/centres/drdc-atlantic-rddc-atlantique/...)
research-technology-recherche-technologie/underwater-sensing-detection-sous-marine.

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

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PUBLICATIONS

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

- Charles W. Holland and Dale D. Ellis. Clutter from non-discrete seabed structures. *J. Acoust. Soc. Am.*, 131(6):4442–4449, 2012. [refereed, published]
- Dale D. Ellis. Calculations of reverberation and fathometer returns at short times using a straight-line ray-path model. Technical Memorandum TM 2011-323, DRDC Atlantic, Dartmouth, NS, Canada, February 2012. 40 pp. [published]
- John R. Preston and Dale D. Ellis. An adiabatic normal mode reverberation and clutter model. In *Proceedings of the 11th European Conference on Underwater Acoustics*, pages 239–246, 2012. Conference held in Edinburgh, Scotland, UK, 2–6 July 2012; file p48.pdf on CD. [published]
- Dale D. Ellis, John R. Preston, and Gary H. Brooke. Progress on the DRDC Clutter Model. In *Proceedings of the 11th European Conference on Underwater Acoustics*, pages 1490–1497, 2012. Conference held in Edinburgh, Scotland, UK, 2–6 July 2012; file p274.pdf on CD. [published]
- Dale D. Ellis and Sean P. Pecknold. Reverberation and target echo calculations for range-dependent sonar problems. In *Proceedings of the 11th European Conference on Underwater Acoustics*, pages 1543–1550, 2012. Conference held in Edinburgh, Scotland, UK, 2–6 July 2012; file p287.pdf on CD. [published]
- Michael A. Ainslie, Mario Zampolli, and Dale D. Ellis. The Weston Memorial workshop: Progress to date on the low frequency active sonar scenarios. In *Proceedings of the 11th European Conference on Underwater Acoustics*, pages 1816–1819, 2012. Conference held in Edinburgh, Scotland, UK, 2–6 July 2012; file p345.pdf on CD. [published]
- Michael A. Ainslie, Dale D. Ellis, and Chris H. Harrison. Low frequency bottom reverberation in a Pekeris waveguide with Lambert’s rule. *J. Comp. Acoust.* [refereed, submitted]