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Measurements and Analysis of Reverberation, Target Echo, and Clutter: FY09 Annual Report for ONR

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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 Principal Investigator (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 took place in 2009. The data from these 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. Although not part of ONR funding, when opportunity presents itself, the improved models will be used in DRDC Technology Demonstrators for the Canadian Forces.

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, the follow-on trial BASE '07, and

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the Clutter ’09 trial in May 2009. All took place on the Malta Plateau, although the BASE ’07 trial included two other areas south of Sicily. The PI participated in the 2007 trials. The current project emphasizes examination and 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, 7]. 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 [8, 9, 10] 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 [11]. The model is also being 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 [12, 13]. A paper with Holland has been published [14], and the paper with Ainslie is in progress. 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 (MREA) 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 MREA 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 [15], and two papers on the measurement and modeling methodology have been accepted and are in press [2, 3]. In 2009, the first paper was expanded as a DRDC Report [16] to include details of the measurement and data processing, and to include a description of the reverberation data files.

The PI participated in the Reverberation Modeling Workshops (RMW) 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 on 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 normal-mode formulation [4] and the Westwood ORCA model [17, 18]. Results were submitted in March 2007 for publication in the Workshop Proceedings, as well as being published as DRDC Technical Memoranda [5, 11]. 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 [9].

Follow-on work on RMW 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 [13], and a journal paper is in progress. Sub-bottom scattering from the collaboration with Holland [14] is now an option in the NOGRP model.

During the past year the modeling focus has been on short times; e.g., ranges less than about 10 water depths, where the fathometer returns and steep-angle reverberation are important. The normal-mode results were extended to short times and submitted to the organizers for comparison with other mode models, and ray-model predictions. A problem that generated a great deal of discussion was RMW Problem 6, for the rough bottom with the summer sound speed profile. It is expected that the organizers will make presentation on the results at the October 2009 meeting of the Acoustical Society of America [19].

To investigate the short-time reverberation, a refinement of a 1986 straight-line ray trace model [20] was developed and implemented. This also required a careful look at the RMW pulse definition. Both of these are discussed in more detail in the "Results" section below.

The equations for the fast reverberation and target echo models were extended in 2008 to handle bistatic geometry and range dependence [6]. Matlab code was developed and calculations performed for bistatic geometry. Range-dependent reverberation and clutter features could be included, but the propagation was only range independent. In 2009 a model that includes range-dependent propagation produced promising initial results [7]. An example is shown in the "Results" section below.

The volume reverberation and target echo components [21] of the model are being exercised on the 2008 RMW 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. A presentation is to be made at the October 2009 meeting of the Acoustical Society of America [22].

Work is progressing at incorporating multiple radials, beam patterns, and target echo into the range-dependent model, to enable comparisons with data, particularly from the Clutter '07 and Clutter '09 trials.

RESULTS

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

Reverberation Modeling Workshop – Pulse shape

A great deal of confusion surrounded the pulse definition for the ONR Workshops. The pulse was specified to be a Gaussian shaded time series. To help clarify the issue, a short note [D. D. Ellis, "That Doggone Pulse", 25 June 2009] was circulated to a number of interested people, and made available for posting to the Workshop FTP site.

The pulse pressure time series (with $A_G = 1\mu$Pa at 1 m for the RMW problems) is given by

$$p(t) = A_G \cos(\omega_0 t) \exp\left(-\frac{1}{2}\left(t\Delta\omega\right)^2\right),$$

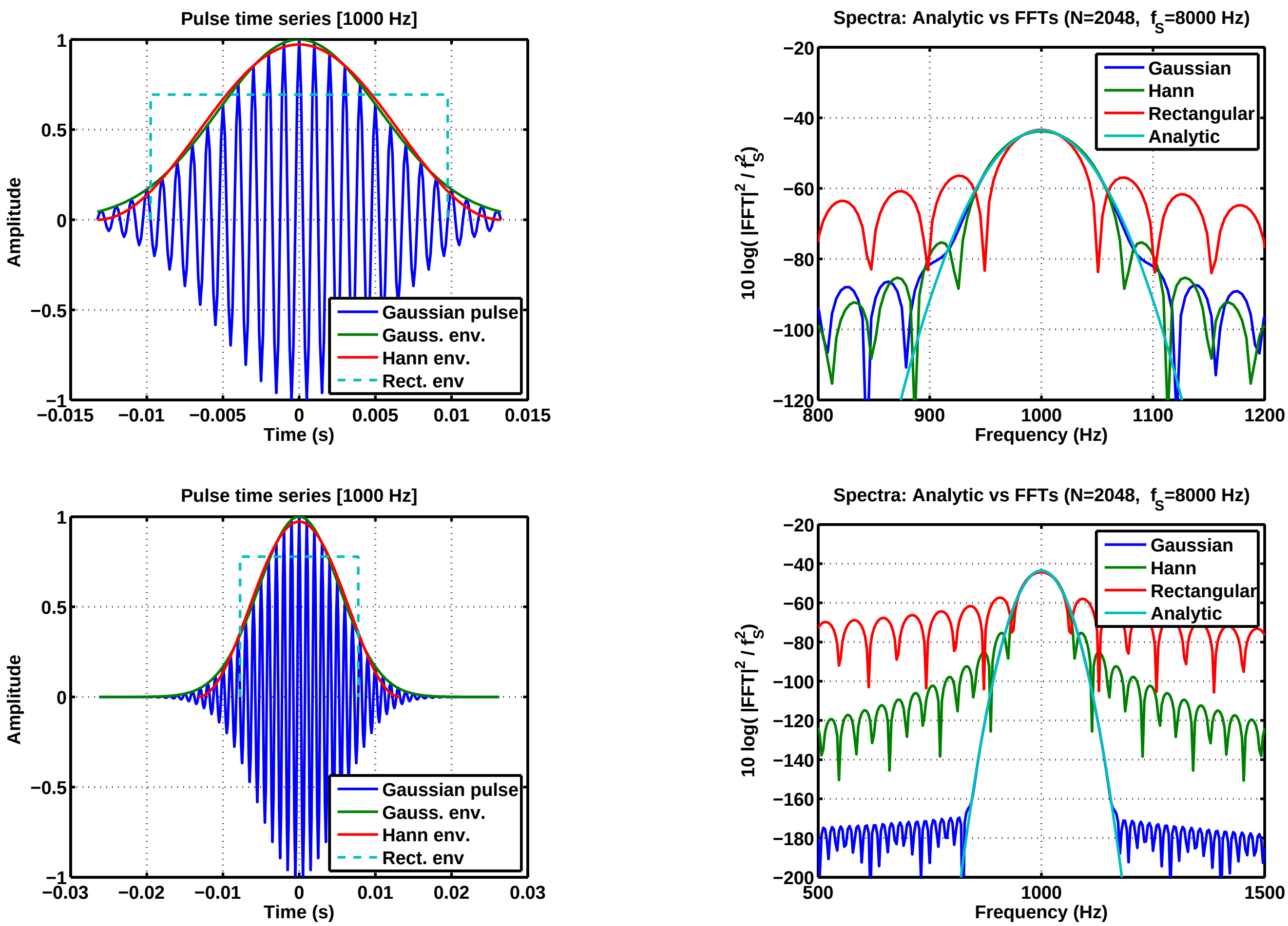

Figure 1. Time series and spectra for several realizations of the ONR pulse at 1 kHz. The upper left figure is for a Gaussian truncated at 26.5 cycles, and the lower left for a Gaussian truncated after 52.5 cycles. The envelopes for a 26.5 cycle Hann weighted pulse are included, as well as for a uniform envelope of 19.5 cycles (upper figure) and 15.5 cycles (lower figure). The corresponding spectra are shown in the right figures.

where $\omega_0 = 2\pi f_0$, f_0 is the centre frequency, and

$$\Delta\omega = \pi B_{3dB}/\sqrt{\ln 2},$$

where B_{3dB} is the total bandwidth to the -3 dB points. Since this pulse is of infinite duration, some truncation will have to occur in any practical calculation. Sonar models commonly use a uniform weighting or a Hann (cosine squared) weighting for the pulse shape.

Figure 1 illustrates the time series and spectra for a number of realizations of the pulse, with $B_{3dB} = f_0/20$. The upper pair of plots illustrate the Gaussian shaded pulse truncated at 26.5 cycles, a Hann envelope of the same duration, and the envelope for a uniform weighting with 19.5 cycles (which corresponds to a duration of approximately 1/bandwidth). All pulses have the same energy in the pulse, so will produce the same average reverberation level at long ranges. The plots on the right show that the Hann-shaded pulse reproduces the main lobe of the analytic spectrum quite closely, but the width of the main lobe for the rectangular window is too narrow. The lower plot of Fig. 1 shows the Gaussian pulse extended to 52.5 cycles. The Hann window is the same as for the upper figure, and the uniform weighting has been shortened to 15.5 cycles to better match the peak of the Gaussian spectrum. Note how extending the Gaussian from 26.5 cycles to 52.5 cycles has reduced the sidelobes by over 80 dB.

The details of the pulse shape are not important for the long-range reverberation, but for short times and target echo problems, the details can be significant.

Fathometer returns and short-range reverberation

At short times/ranges the fathometer returns and steep-angle reverberation become important. Normal-mode models are not particularly well suited in this regime, since the branch line integral contributes, and the solution for a number of frequencies needs to be convolved with the source spectrum to produce a time series. A straight-line ray model, combined with the source pulse shape, should give a good approximation to reverberation, at least where the single scattering formulation is valid. A program `Becky_rvb` was developed to convolve the source pulse with the reverberation intensity for an impulse response, and to coherently combine the fathometer returns. The details of the pulse shape are important, since the multiple fathometer returns overlap.

Figure 2 shows fathometer returns and short-range reverberation for RMW Problem 11: 100 m of isovelocity water, with Lambert bottom scattering. The upper plot compares the NOGRP (normal mode) predictions with the predictions from `Becky_rvb` at 1 kHz, for the 30 m source and 50 m receiver. The two are in quite good agreement at 2 s (and beyond), with the ray-trace being calculations slightly higher as one would expect since there should be a small contribution from angles above the critical angle. At shorter times, the effect of the steeper angles becomes increasingly significant. The `Becky_rvb` calculations were done allowing 7 bottom bounces or 20 bottom bounces on the outgoing and return paths; 7 bottom bounces seem sufficient out to 1 s. The lower envelope of the curve essentially delimits the reverberation, while the peaks are from the fathometer returns.

The lower plot of Fig. 2 compares the predictions at 3 frequencies, but for a receiver at 10 m. Here we see that for the 3500 Hz pulse the fathometer returns are resolved, while at 250 Hz there is considerable overlap. At 1 kHz, some pairs are barely resolved. The 1 kHz case can be compared with the upper plot for the 50 m receiver; the reverberation levels are similar, but the details of the fathometer returns are quite different.

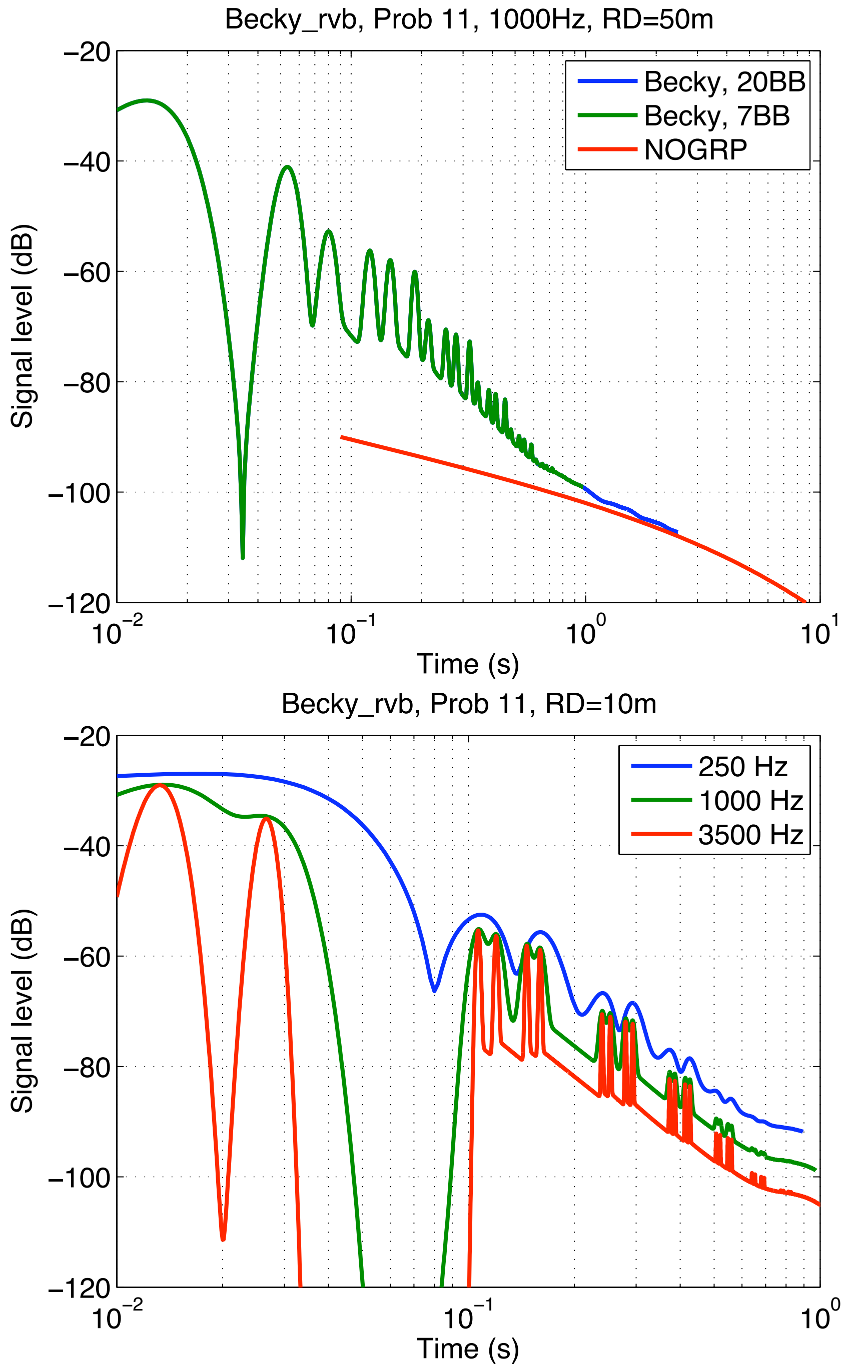

Figure 2. Ray-trace predictions of fathometer returns and short-range reverberation at two receiver depths for RMW Problem 11.

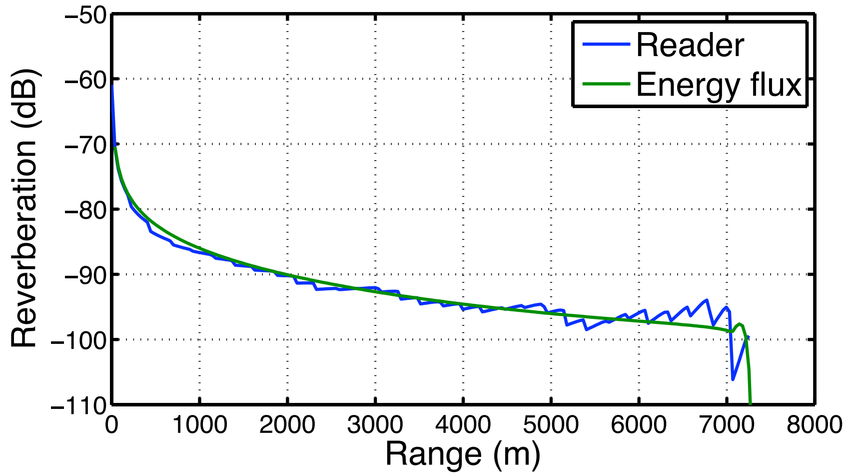

Figure 3. Reverberation at 250 Hz along an up-slope radial; the water depth is 200 m at zero range, reducing to zero depth at a range of 7400 m.

Range-dependent reverberation using adiabatic modes

A formulation, based on adiabatic normal modes, was developed in 2008 for range-dependent reverberation and target echo over an area [6]. During the summer of 2009, a Matlab script was developed to perform the reverberation calculations along a radial [7]; a correction [23] to the scattering area is also incorporated. The normal modes were calculated at various points along the radial using the Fortran code PROLOS [24], and the reverberation calculations and plotting were performed using the Matlab script `Reader`.

Figure 3 shows results from the steepest up-slope radial for RMW Problem 17 at 250 Hz using 200 points along the radial. The environment is a wedge of isovelocity water, with the depth going from 200 m at zero range to 0 depth at range 7400 m; the bottom has Lambert scattering. The irregular curve of the normal mode reverberation is due to mode cutoff. The smoother curve is from a energy flux calculation by Harrison [25, 26]. These results are preliminary and need further validation. It is also necessary to incorporate multiple radials and towed array beam patterns for comparison with reverberation and clutter data.

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) [27, 28] 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 behind the unidentified clutter on a display. These unidentified features would then be investigated by other techniques to try to determine their nature.

TRANSITIONS

The range-dependentreverberation and target echo model is targeted to be part of a clutter model for the DRDC Pleiades System, which is used in some Canadian Forces exercises. An initial research contract to incorporate the reverberation and target echo was completed by General Dynamics of Canada Limited in March 2009, and a follow-on contract proposal was submitted in July 2009, and is currently awaiting funding.

The David Weston Sonar Performance Assessment Symposium, Cambridge, UK, 7–9 April 2010 will have a number of sonar scenarios. At least one of these will be based on the Reverberation Modeling Workshop problems, extended to the complete sonar problem. The driving force behind the sonar modelling is the Low Frequency Active Sonar program of TNO and the Royal Netherlands Navy.

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.

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PUBLICATIONS

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- John R. Preston and Dale D. Ellis. Extracting bottom information from towed-array reverberation data Part I: Measurement methodology. *J. Mar. Syst.*, 2009. In press; doi:10.1016/j.jmarsys.2009.01.034. [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. Mar. Syst.*, 2009. In press; doi:10.1016/j.jmarsys.2009.01.035. [in press, refereed]
- John R. Preston and Dale D. Ellis. Extracting bottom information from towed-array reverberation data: Measurement methodology. DRDC Atlantic Technical Report TR 2009-042, DRDC Atlantic, Dartmouth, NS, Canada, September 2009. [in press]