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Final Report for ONR Grant N00014-06-1-0830: Measurements and Analysis of Reverberation, Target Echo and Clutter

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DRDC Atlantic ECR 2012-274
December 2013

Canada

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Abstract

This is the final report for US Office of Naval Research (ONR) for Grant N00014-06-1-0830: “Measurements and Analysis of Reverberation, Target Echo and Clutter.” A brief overview of the objectives and approach is given, followed by a summary of the accomplishments and publications for the period 2006–2011. Future directions and potential operational impact and transitions are mentioned.

Résumé

Voici le rapport définitif à l’intention de l’Office of Naval Research (ONR) des États-Unis pour la subvention N00014-06-1-0830 : “Measurements and Analysis of Reverberation, Target Echo and Clutter” (Mesures et analyse de la réverbération, des échos de cible et du fouillis d’écho). On donne un aperçu des objectifs et de la démarche adoptée, ainsi qu’un résumé des réalisations et des publications pour la période de 2006 à 2011. On aborde aussi les directions futures et les incidences et les transitions opérationnelles possibles.

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Executive summary

Final Report for ONR Grant N00014-06-1-0830: Measurements and Analysis of Reverberation, Target Echo and Clutter:

Dale D. Ellis; DRDC Atlantic ECR 2012-274; Defence R&D Canada – Atlantic; December 2013.

Background: This is the final report for US Office of Naval Research (ONR) for Grant N00014-06-1-0830: "Measurements and Analysis of Reverberation, Target Echo and Clutter." Each year the Principal Investigator (PI) spends two to three months per year at the Applied Research Laboratory of The Pennsylvania State University, funded by ONR. Also, each year a short Annual Report is submitted to ONR. This report provides a summary for the full 5-year period of the grant 2006–2011.

Principal results: The project was part of a joint collaboration between Defence Research and 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. The primary outputs of the collaboration were manuscripts for joint publications in conference proceedings and refereed journals. Secondary outputs were improved models and algorithms.

Overall, the main accomplishments of the five-year period were: (i) submission and publication of a pair of journal papers on the reverberation Rapid Environmental Assessment Methodology that had been the focus of measurement and modeling efforts over the previous decade; (ii) participation in the Reverberation Modeling Workshops, and the development of benchmark solutions for some of the problems; (iii) extension of the fast reverberation modeling approach to handle range-dependent environments and bistatic geometry; (iv) development of a Clutter Model for direct comparison with towed array beam time series in a range-dependent clutter environment; (v) initial work on modeling target echo and time spreading of the target echo; (vi) extension of the normal-mode reverberation modelling approach to handle sub-bottom reverberation, including range-dependent environments; (vii) design of experiments, participation in sea trials, model-data comparisons, and analysis of towed array reverberation and clutter data. The year-by-year accomplishments are listed in the "Main Accomplishments" section of the report.

Significance of results: 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, target echo, and clutter in shal-

low water environments, and to develop techniques for Rapid Environmental Assessment (REA) and environmentally adaptive sonar.

The PI and his main collaborator Dr. John Preston had participated in the pioneering work on REA with SACLANTCEN and NATO MILOC. That effort had been the focus of measurement and modeling efforts over the previous decade, and they had presented a number of invited talks and papers. However, a complete description of the methodology had not been documented; the pair of journal papers provided a fairly complete description of both the measurement and the modeling methodology used, and a DRDC report provided additional details.

A key to the REA work was a fast reverberation model developed as a computationally-efficient tool to compare model predictions with measured reverberation and clutter data from a towed array. As a potential operator tool, one can subtract the predictions, including range-dependent effects and known scattering features, from the data, leaving the differences as unidentified clutter features on a display. These unidentified features can then be investigated by other techniques to try to determine their nature.

The initial reverberation model was normal-mode based and for a flat bottom environment. During the period of the grant, to allow for better comparison with data, the model was extended to range-dependent environments, bistatic geometry, and to handle target echo and scattering from clutter objects. A Clutter Model was developed and used to compare with towed array data, not just a beam at a time along a single radial, but for the full set of beams over an area. A very useful feature of the Clutter Model formulation is that the computational engine is a subroutine, rather than a standalone program. This facilitates its inclusion in other applications. Initial work has been done to include it in the DRDC System Test Bed (a version of which goes to sea with the Canadian Forces).

The dominant source of reverberation can be scattering from a sub-bottom interface, rather than the seabed itself. Furthermore, when this interface is sloped, the sub-bottom clutter mechanism may be a viable hypothesis for areas where target-like clutter has been observed, but no discrete features, buried or proud, can 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., returns that are due to discrete objects.

An important component of modeling is validation against benchmarks. The PI actively participated in the ONR Reverberation Modeling Workshops and the UK Workshop on Validation of Sonar Performance Tools, providing solutions and helping to develop and refine the test problems. With other colleagues he submitted journal article providing a benchmark solution for the flat bottom case. More recent work using adiabatic normal modes addresses the range-dependent cases. The predictions for the range-dependent test problems seem to be the first predictions published, and give a starting point for more accurate solutions.

Future work: Determining the limits of the adiabatic normal mode approach is an important research question.

Target echo modelling needs to be investigated further, particularly with respect to multipath effects.

Many of the techniques developed under this collaborative project could be useful for the recently approved DRDC Technical Demonstration Project AMASE (Advancing Multistatic Active Sonar Employment).

A standalone version of the Clutter Model with public domain databases and a Java GUI was developed by Brooke Numerical Systems in 2010 and extended in 2012. The hope is to be able to implement the Clutter Model as a tactical tool.

A critical component of the effort is the quantitative comparison of model predictions with experimental data, both for the understanding and interpretation of the data, and validation of the models. A key component of this is the 2013 ONR Target and Reverberation Experiment in which DRDC participated with their Research Vessel Quest. The PI will be fully engaged with the analysis and quantitative modeling of the reverberation experiments.

Sommaire

Final Report for ONR Grant N00014-06-1-0830: Measurements and Analysis of Reverberation, Target Echo and Clutter:

Dale D. Ellis ; DRDC Atlantic ECR 2012-274 ; R & D pour la défense Canada – Atlantique ; décembre 2013.

Introduction : Voici le rapport définitif à l'intention de l'Office of Naval Research (ONR) des États-Unis pour la subvention N00014-06-1-0830 : "Measurements and Analysis of Reverberation, Target Echo and Clutter" (Mesures et analyse de la réverbération, des échos de cible et du fouillis d'écho). Chaque année, le chercheur principal (CP) passe de deux à trois mois à l'Applied Research Laboratory de l'Université d'État de Pennsylvanie, dans le cadre d'un projet de recherche financé par l'ONR. Nous présentons aussi un court rapport annuel à l'ONR. Le présent rapport donne un résumé pour la période complète de cinq ans de la subvention, de 2006 à 2011.

Principaux résultats : Le projet s'inscrivait dans le cadre d'une collaboration entre Recherche et développement pour la défense Canada – Atlantique (RDDC Atlantique) et l'Applied Research Laboratory de l'Université d'État de Pennsylvanie qui visait à analyser et à modéliser la réverbération, les échos de cible et le fouillis acoustique en eaux peu profondes. Les principaux résultats de la collaboration étaient des manuscrits aux fins de publication conjointe dans des comptes rendus de conférence et des revues à comité de lecture. Les résultats secondaires étaient des modèles et des algorithmes améliorés.

Voici un aperçu des principales réalisations au cours de ces cinq ans : (i) présentation et publication d'une paire d'articles de revue sur la méthode d'évaluation environnementale rapide de la réverbération qui a fait l'objet d'efforts de mesure et de modélisation au cours des 10 années précédentes ; (ii) participation aux ateliers sur la modélisation de la réverbération et élaboration de solutions de base pour certains problèmes ; (iii) élargissement de la démarche de modélisation rapide de la réverbération pour prendre en charge les environnements dont les caractéristiques varient fortement en fonction de la distance ainsi que la géométrie bistatique ; (iv) élaboration d'un modèle de fouillis acoustique pour permettre la comparaison directe des résultats aux séries temporelles de mesures de faisceaux de réseaux remorqués dans un environnement dont les caractéristiques varient fortement en fonction de la distance ; (v) travaux initiaux de modélisation de l'écho de la cible et de la dispersion temporelle de cet écho ; (vi) élargissement de la méthode de modélisation de la réverbération en mode normal pour prendre en charge la réverbération du sous-sol du fond, y compris dans les environnements dont les caractéristiques varient fortement en fonction de la distance ; (vii) conception d'expériences, participation à des essais en mer, comparaison des données de modèles et analyse des données de réverbération et de fouillis acoustique de réseau remorqué. Les réalisations par année figurent dans la section Main Accomplishments (principales réalisations) du rapport.

Importance des résultats : Sur le plan opérationnel, le fouillis acoustique est considéré l'un des problèmes les plus importants relatifs à l'utilisation de sonars actifs en eaux peu profondes. L'objectif à long terme des travaux est de mieux comprendre et modéliser la réverbération, les échos de cible et le fouillis acoustique en eaux peu profondes et d'élaborer des techniques d'évaluation environnementale rapide (REA) et une technologie sonar qui s'adapte à l'environnement.

Le CP et son principal collaborateur, monsieur John Preston, Ph.D, ont collaboré aux travaux novateurs sur la REA avec SACLANTCEN et le groupe MILOC de l'OTAN. Ce projet a fait l'objet d'efforts de mesure et de modélisation au cours des 10 dernières années, et le CP et monsieur Preston ont présenté des exposés sur invitation et des articles. Par contre, une description complète de la méthodologie n'avait pas été consignée ; les deux articles de revue spécialisée ont décrit assez complètement la méthode de mesure et de modélisation utilisée et un rapport de RDDC a ajouté d'autres renseignements.

Un élément clé des travaux de RED était un modèle rapide de réverbération mis en oeuvre sous forme d'un outil informatique efficace afin de comparer les prédictions du modèle avec des mesures de réverbération et de fouillis acoustique provenant d'un système à réseau remorqué. Un outil possible permettrait de soustraire des données les prédictions, y compris les effets qui varient en fonction de la distance et les caractéristiques de diffusion connues, et d'afficher les différences comme caractéristiques de fouillis non identifiées. On pourrait alors examiner ces caractéristiques non identifiées au moyen d'autres techniques pour en déterminer la nature.

Le modèle de réverbération initial fonctionnait en mode normal, pour un fond plat. Au cours de la période de la subvention, pour permettre une comparaison améliorée avec les données, le modèle a été étendu aux environnements dont les caractéristiques varient avec la distance et de manière à traiter les échos d'objectifs et la dispersion provenant d'objets parasites. Un modèle de fouillis acoustique a été élaboré et utilisé aux fins de comparaison avec des données provenant d'un réseau remorqué, non seulement pour un seul faisceau selon un seul trajet radial, mais pour un ensemble complet de faisceaux dans une zone. Une caractéristique très utile de la mise en oeuvre du modèle de fouillis acoustique est que le moteur de calcul est une sous-routine plutôt qu'un programme autonome. On peut donc facilement l'intégrer à d'autres applications. Des travaux initiaux ont été effectués pour l'intégrer dans le banc d'essai du système de RDDC (une version de celui-ci accompagne les Forces canadiennes en mer).

La principale source de réverbération peut être la dispersion provenant de l'interface du sous-sol de fond plutôt que du fond marin lui-même. De plus, lorsque ce sous-sol est incliné, un mécanisme de fouillis acoustique provenant du sous-sol peut expliquer certaines zones qui présentent un fouillis semblable à celui d'une cible sans qu'on puisse y trouver de caractéristiques particulières, souterraines ou en saillie. Grâce à l'utilisation d'une source à large bande, l'évolution temps-fréquence du fouillis acoustique permettrait de distinguer cette source de fouillis d'autres sources, par exemple des objets discrets.

Un élément important de la modélisation est la validation des résultats du modèle par rapport à des données de base. Le CP participe activement aux ateliers de modélisation de la réverbération organisés par l'ONR et à l'atelier sur la validation d'outils d'évaluation du rendement sonar (Validation of Sonar Performance Assessment Tools) du R.-U., dans le cadre desquels il offre des solutions et aide à définir et à raffiner les problèmes d'essais. En collaboration avec des collègues, il a soumis un article de revue qui donnait une solution de base pour les fonds plats. Des travaux plus récents utilisant des modes normaux adiabatiques traitent les cas où les caractéristiques varient avec la distance. Nous semblons être les premiers à rendre publiques des prévisions relatives aux problèmes d'essai de portée acoustique ; celles-ci sont donc un bon point de départ en vue de l'élaboration de solutions plus fidèles.

Travaux à venir : L'établissement des limites du mode normal adiabatique constitue un domaine de recherche important.

Nous devrons effectuer d'autres recherches sur la modélisation de l'écho de la cible, particulièrement en ce qui concerne les effets de la propagation multitrajets.

Plusieurs techniques élaborées dans le cadre de notre projet collaboratif pourraient se révéler utiles dans le cadre du projet AMASE, récemment approuvé, de démonstration technique de RDDC en vue d'améliorer l'emploi de sonars actifs multistatiques.

Brooke Numerical Systems a créé en 2010 une version autonome du modèle de fouillis acoustique, qui exploite des bases de données publiques et est munie d'une interface graphique en Java, et l'a amélioré en 2012. Nous espérons faire de ce modèle un outil tactique.

Un élément essentiel de nos travaux est la comparaison quantitative des prévisions du modèle aux données expérimentales afin de comprendre les données et d'être en mesure de les interpréter ainsi que de valider les modèles. Une étape clé a été l'expérience ≪ Target and Reverberation Experiment ≫ de l'ONR en 2013, à laquelle RDDC a participé avec son navire de recherche Quest. Le CP sera responsable de l'analyse de la modélisation quantitative des résultats des expériences de réverbération.

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1 Introduction

This is the final report for US Office of Naval Research (ONR) for Grant N00014-06-1-0830: “Measurements and Analysis of Reverberation, Target Echo and Clutter.” A brief overview of the objectives and approach is given, followed by a summary of the accomplishments and publications for the period 2006–2011. Future directions and potential operational impact and transitions are mentioned.

2 Overview

From an operational perspective, clutter is viewed as one of the most important problems facing active sonar in shallow water. 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.

2.1 Objectives

The project was part of a joint collaboration between Defence Research and 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. The collaboration leverages programs in Canada and the US, and 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.

Central to this collaboration have been Joint Research Projects (JRPs) between CMRE, Canada and several US research laboratories (ARL in particular). An important part of the JRPs has been sea trials, conducted in 2001, 2002, 2004, 2007 and 2009. The initial JRP was the 2000–2004 “Boundary Characterization”, results of which were summarized in the IEEE Journal of Oceanic Engineering Special Issue on “Interaction of Low- to Mid-Frequency Sound with the Ocean Bottom” [1].

The period covered by this report covers the 2006–2010 JRP “Characterizing and Reducing Clutter for Broadband Active Sonar”. The PI participated in the Clutter ’07 and BASE ’07 Mediterranean sea trials with NURC; the PI did not directly participate in the Clutter ’09 sea trial, but helped plan some experiments and worked with some of the data with John Preston from ARL/PSU. One focus is the performance of directional sensors in towed arrays.

Another focus has been the development and validation of a fast shallow-water sonar model that includes target echo and clutter. It is suitable for comparison with the experimental data from the towed array, and has been extended to bistatic capability and range dependence. In addition to comparison with data, 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.

2.2 Approach

The Principal Investigator (PI) spent two to three months per year at ARL/PSU, conducting joint research primarily with Dr. John Preston and Dr. Charles Holland. Additional collaboration took place throughout the year. The main objective of this collaboration was to analyze, model, and interpret data received on towed arrays during reverberation and clutter sea trials. The primary outputs of the collaboration were manuscripts for joint publications in conference proceedings and refereed journals. Secondary outputs were improved models and algorithms.

The ONR Reverberation Modeling Workshops (RMW) [2, 3, 4] have been a focus for collaboration, have stimulated further work; e.g., the 2010 Symposium on Validation of Sonar Performance Assessment Tools [5] (sometimes referred to as the Weston Memorial Workshop), sponsored by the UK Institute of Acoustics. 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).

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” [6, 7] 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 [7] in support of the GulfEx12 and TREX13 experiments [8].

3 Main accomplishments

Each year a short Annual Report is submitted to ONR. This section summarizes some of the main accomplishments during the period 2006–2011.

Overall, the main accomplishments of the five-year period were:

- submission and publication of a pair of papers on the reverberation Rapid Environmental Assessment methodology that had been the focus of measurement and modeling efforts over the previous decade;
- participation in the Reverberation Modeling Workshops, and the development of benchmark solutions for some of the problems;
- extension of the fast reverberation modeling approach to handle range-dependent environments and bistatic geometry;
- development of a Clutter Model for direct comparison with towed array beam time series in a range-dependent clutter environment;
- initial work on modeling target echo and time spreading of the target echo;
- extension of the normal-mode reverberation modelling approach to handle sub-bottom reverberation, including range-dependent environments;
- design of experiments, participation in sea trials, model-data comparisons, and analysis of towed array reverberation and clutter data.

Further detail is in the annual reports: [9, 10, 11, 12, 13]. The publications for the period are listed in Section 5. The year-by-year accomplishments, more or less as originally written, are listed in the sub-sections below.

3.1 Summary of work completed 2006–2007

The main accomplishments for the year were: (i) participated in the Reverberation Modeling Workshop in Austin, Texas, in November 2006; (ii) applied models to a number of Workshop problems, collaborated with Preston in developing a Matlab-based reverberation model, and submitted results for Workshop proceedings; (iii) began collaboration with Ainslie and Harrison to develop benchmark solution for RMW Problem 11; (iv) extended the normal mode model to handle subbottom scattering and collaborated with Charles Holland to verify his energy flux approach; (v) participated in the Clutter '07 and Base '07 sea trail in the Mediterranean; (vi) completed a paper on comparing cardioid and limaçon sensor in towed arrays; and (vii) initiated work on a pair of papers on the measurement and modeling approach to using reverberation for REA. Some details are given below and in Ref. [9].

The PI participated in the Reverberation Modeling Workshop in Austin in November 2006. He applied his normal mode models OGOPOGO/NOGRP to a number of problems, and collaborated with Preston in developing a Matlab-based model using the PI's normal-mode formulation [14]. Results were submitted in March 2007 for publication in the Workshop Proceedings [15]; the Proceedings was delayed, so the reports were later published as DRDC Technical Memoranda [16, 21]. Follow-on collaborations with Ainslie and Harrison lead to presentations at a Special Session of the Acoustical Society of America in November 2007 [17], and a journal manuscript initiated.

In collaboration with John Preston a bistatic version of the fast normal-mode approach was implemented using the ORCA normal-mode model [18] together with Matlab scripts for the reverberation calculations. Comparisons were made with NOGRP/Rosella and the Generic Sonar Model [19] for a few simple test cases. More comparisons were made, and results presented at the ONR Reverberation Modeling Workshop in Austin in November 2006. Results were presented at the ONR Reverberation Modeling Workshop in 2006, and submitted in March 2007 [20, 21] for publication in the Workshop Proceedings, as well as presented at the Underwater Acoustic Measurements conference in 2007 [22].

The normal-mode reverberation model was extended to handle scattering from a sub-bottom interface. Collaboration with Charles Holland has led to a comparison of the normal-mode and energy flux approaches. A paper was submitted to the Journal of Computational Acoustics [23], and some results presented at the Special Session on Reverberation Modeling at the November 2007 meeting of the Acoustical Society of America [24].

Work has continued on extending the fast reverberation model to handle target echo and signal excess, including the effects of time spreading. An invited presentation [25] was given at the 8th International conference on Theoretical and Computational Acoustics in Crete in July 2007.

The PI sailed on R/V Oceanus for the Clutter '07 sea trial and the first portion of the BASE '07 sea trial, both in the Mediterrean. Emphasis was on data acquisition, so it was not possible to analyze much data. However, the PI became familiar with the FORA processing chain, identified problems with some of the matched filter designs; he also developed a Matlab procedure for easily overlaying data on contours and clutter features.

Work continued on comparing the effects of linear and triplet arrays on reverberation measurements. A comparison was made between the effect of cardioid sensors versus limaçon sensors on reverberation received on a towed array [26]. An invited paper was presented at the Underwater Acoustics Measurements, in Heraklion, Greece, in June 2007 [27].

The September 2007 REA Conference in Lerici, Italy, has provided impetus in completing a pair of journal articles summarizing the reverberation work during the 1996–1998 Rapid Response Exercises and follow-on JRPs with NURC. A poster presentation was presented at the conference [28], and two papers on the measurement and modeling methodology prepared.

3.2 Summary of work completed 2007–2008

The main accomplishments for the year were: (i) submission and acceptance of a pair of papers on the reverberation Rapid Environmental Assessment methodology of Ellis and Preston, (ii) work on the ONR Reverberation Modeling Workshop problems and publication of internal reports, (iii) additional work on fast reverberation model and acceptance of paper on reverberation from a sub-bottom interface; and (iv) extension of the formulation for reverberation modeling to bistatic and range-dependence, and publication of initial results for the bistatic case. Some details are given below and in Ref. [10].

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 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 [28], and two papers on the measurement and modeling methodology were accepted for publication [29, 30].

The PI participated in the Reverberation Modeling Workshops at Austin, Texas, 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 normal-mode formulation [14] and the Westwood ORCA model [18, 31]. Results were submitted in March 2007 for publication in the Workshop Proceedings. That publication was delayed, so the contributions were published as DRDC Technical Memoranda [16, 21]. The normal-mode method compared quite well with other results, and seems to have been used to calibrate a number of other models 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 [3].

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 [17], 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 of Ref. [10].

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 [24], and a paper has been accepted by the Journal of Computational Acoustics [23]. 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 [14] inadvertently omitted a density factor in the normal mode propagation term [32]. 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 [33] 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 [34]. It is a generalization of the energy-flux approach of Harrison [35]. Matlab code has been developed and calculations performed for bistatic geometry; an example is given in the "Results" section of Ref. [10]. 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 [29, 30]. The extension to bistatic range-dependence is formulated in [34]. 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 of Ref. [10]. 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.

3.3 Summary of work completed 2008–2009

The main accomplishments for the year were: (i) final tweaks of a pair of journal papers by Ellis and Preston on the Rapid Environmental Assessment (REA) reverberation methodology, and adding more details on the data acquisition and processing for publication as a DRDC report, (ii) additional work on the ONR Reverberation Modeling Workshop problems with emphasis on short times; (iii) development of a ray-trace reverberation code to calculate short-time reverberation and fathometer returns; and (iv) development a range-dependent reverberation model based on adiabatic modes and initial testing on a number of problems. Some details are given below and in Ref. [11].

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 [28], and two papers on the measurement and modeling methodology have been accepted and are in press [36, 37]. In 2009, the first paper was expanded as a DRDC Report [38] 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, Texas, 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 [14] and the Westwood ORCA model [18, 31]. Results were submitted in March 2007 for publication in the Workshop Proceedings, as well as being published as DRDC Technical Memoranda [16, 21]. The normal-mode method compared quite well with other results, and seems to have been used to calibrate a number of other models 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 [3].

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 [17], and a journal paper is in progress. Sub-bottom scattering from the collaboration with Holland [23] is now an option in the NOGRP model.

During the past year the modeling focus for the RMW 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 PI's 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 present results at the October 2009 meeting of the Acoustical Society of America [39].

To investigate the short-time reverberation, a refinement of a 1986 straight-line ray trace model [40] 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 of

Ref. [11].

The equations for the fast reverberation and target echo models were extended in 2008 to handle bistatic geometry and range dependence [34]. 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 [41].

The volume reverberation and target echo components [33] 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 [42].

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.

3.4 Summary of work completed 2009–2010

The main accomplishments for the year were: (i) completion of a report on monostatic reverberation calculations over a sloping bottom; (ii) development of a bistatic range dependent clutter model that includes towed array beam patterns; (iii) calculations of time spreading of scattering features and target echo and their effect on signal excess; (iv) additional work on fathometer returns and reverberation at short times. The most significant accomplishment was the bistatic range-dependent clutter model based on adiabatic modes. It is computationally efficient and an initial version is working on a Windows platform; a Unix version is being implemented in the DRDC System Test Bed for potential use by the Canadian Forces. Some details are given below and in Ref. [12].

The ONR Reverberation Modeling Workshops have stimulated further work on sonar benchmark problems. One such activity was the 2010 Symposium on Validation of Sonar Performance Assessment Tools, sponsored by the UK Institute of Acoustics in memory of David Weston. One of the “Weston Symposium” problems extended the ONR problems to the full sonar scenario, including matched filter processing, background noise, and signal-to-noise ratio. The main organizer was M. Ainslie of TNO in the Netherlands, and the PI provided advice on the problem definitions, which are now being published formally [43].

During the past year the PI worked on the target echo problem from the 2008 ONR Reverberation Modeling Workshop and the 2010 Weston Symposium. While multipath time spreading is not very important for diffuse reverberation, it can have have a significant effect for feature scattering and target echo [14, 33]. A presentation was made at the October

2009 meeting of the Acoustical Society of America [42], and at the Weston Symposium [44]. An example is shown in the "Results" section of Ref. [12].

The ONR Workshops uncovered differences between model predictions at short times; e.g., ranges less than about 10 water depths, where the fathometer returns and steep-angle reverberation are important. A problem that generated a great deal of discussion was Workshop Problem VI, for the rough bottom with the summer sound speed profile. The PI's normal-mode results were extended to short times and submitted to the organizers for comparison with other mode models, and ray-model predictions. They were included in a presentation at the October 2009 meeting of the Acoustical Society of America [39].

It is difficult to properly include the short range effects in a normal mode model, so, to investigate the short-time reverberation, a refinement of a 1986 straight-line ray trace model [40] was developed and implemented. This also required a careful look at the pulse definition for the Reverberation Modeling Workshop. The results were submitted to the ONR Workshop organizers, and presented at the Weston Symposium [45].

As part of the model development for model-data comparisons, the fast shallow-water reverberation model [14, 16] based on normal modes has been extended to a bistatic, range-dependent clutter model that includes target echo and feature scattering [34, 41, 46]. The formulation based on adiabatic modes had been developed earlier [34] and calculations were done using Matlab for a flat bottom environment. In 2010 the model was converted to Fortran 95, and extended to handle range-dependent bathymetry and scattering. Like the reverberation model, it is computationally efficient and includes the 3-D effects of towed array beam patterns in order to facilitate comparison with experimental measurements. A short paper will appear in Canadian Acoustics [46]. Some results are illustrated in the "Results" section of Ref. [12].

A very useful feature of the clutter model is that it is a subroutine, rather than a standalone program. This facilitates its inclusion in other applications. Work is progressing to include it in the DRDC System Test Bed (a version of which goes to sea with the Canadian Forces); a standalone version with Java GUI and public domain databases is already running on a Windows system [47]. Further model improvements will occur in the next year, applying it to other problems from the ONR Workshops and Weston Symposiums, as well as comparisons with towed array data, particularly from the Clutter '07 and Clutter '09 trials.

3.5 Summary of work completed 2010–2011

The main accomplishments for the year were: (i) enhancements to the PI's Clutter Model, and comparison with towed array data from the Malta Plateau; (ii) providing solutions of reverberation and target echo for several range-dependent problems from the Reverberation Modeling Workshop and UK Symposium on Validation of Sonar Performance Assessment Tools; (iii) extending the adiabatic model to handle range-dependent subbottom scattering;

and (iv) in collaboration with other authors, submission of a journal manuscript comparing analytical techniques, ray theory, energy flux, and normal modes for Problem 11 of the Reverberation Modeling Workshop. Some details are given below and in Ref. [13].

The wrap-up meeting of the JRP "Characterizing and Reducing Clutter for Broadband Active Sonar" was held at NURC in late September 2011. Immediately following it, the initial meeting for the proposed JRP "Modeling and Stimulation for ASW Active Sonar Trainers" was held. The project has been accepted for the NURC program of work for years 2011–2013, but no NURC resources have been yet allocated for 2011.

In collaboration with Michael Ainslie and Chris Harrison, a careful comparison has been made of various predictions for Problem 11 of the 2006 Reverberation Modeling Workshop – a Pekeris environment with Lambert scattering from the bottom. The modeling approaches use analytical techniques, ray theory, energy flux, and normal modes. A presentation on this has been made at the Spring 2011 meeting of the Acoustical Society of America [48], and a journal manuscript was submitted.

As part of the model development for model-data comparisons, the fast shallow-water reverberation model [14, 16] based on normal modes has been extended to a bistatic, range-dependent Clutter Model that includes target echo and feature scattering. This formulation, based on adiabatic modes, was developed in 2008 [34] and example calculations for a flat bottom environment were done using Matlab. In 2010 the model was converted to Fortran 95, and extended to handle range-dependent bathymetry and scattering. Like the fast flat-bottom reverberation model, it is computationally efficient and includes the 3-D effects of towed array beam patterns in order to facilitate comparison with experimental measurements. A short paper describing the model appeared in Canadian Acoustics in 2010 [46], and further enhancements to it were made in 2011. Range-dependent predictions were compared with towed array clutter data from the Malta Plateau, and presented as an invited paper [6] at the 2011 Underwater Acoustic Measurements Conference. This comparison is illustrated in the "Results" section of Ref. [13].

A very useful feature of the Clutter Model formulation is that the computational engine is a subroutine, rather than a standalone program. This facilitates its inclusion in other applications. Work is progressing to include it in the DRDC System Test Bed (a version of which goes to sea with the Canadian Forces). A standalone version with Java GUI and public domain databases [47] was implemented on a Windows system in 2010, and extended to Unix systems in 2011.

Though the Clutter Model is computationally efficient, determining the limits of its adiabatic mode approach is an important research question. In 2011 the PI produced predictions [49] for some range-dependent problems from the Reverberation Modeling Workshop and the Weston Symposium on Validation of Sonar Performance Assessment Tools. To facilitate this, the PI collaborated with John Preston in extending his Matlab/ORCA reverberation model [29] to handle range dependent environments [50]. Examples of these predictions are illustrated in the "Results" Section of Ref. [13]. These seem to be the first range-dependent predictions published, and give a starting point for more accurate solutions.

Even with a smooth bottom, acoustic clutter in the water column can be generated by subbottom effects. Collaboration with Holland has shown that even slowly-varying sediment layers can lead to a large target like response. To facilitate this, the adiabatic mode model was applied to environments with a range-dependent subbottom, and predictions compared with energy flux solutions. A manuscript [51] was submitted, and a presentation made at the Fall 2011 meeting of the Acoustical Society of America [52].

3.6 Future Work

Target echo modelling needs to be investigated further, particularly with respect to time spreading due to multipath effects.

Determining the limits of the adiabatic normal mode approach is an important research question.

A key component of the effort is the quantitative comparison of model predictions with experimental data, both for the understanding and interpretation of the data, and validation of the models.

At the end of the time period for this grant the focus was on experiment design for the ONR mid-frequency reverberation and target echo experiments in the Gulf of Mexico near Panama City, Florida [8]. Since that time the Panama City TREX experiments have taken place. DRDC Atlantic participated, along with their research vessel CFAV Quest. The PI was fully engaged with the experiments, and is actively participating in the follow-on data analysis and quantitative model validation.

4 Potential Applications or 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 REA [53, 54] and environmentally adaptive sonar.

One goal is to be able to use the clutter model with near-real-time 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 due to discrete objects.

4.1 Transitions

Small DRDC research contracts for the Clutter Model implementation were let in 2009, 2010, 2011, and 2012. A standalone version [47] with public domain databases and a Java GUI was developed by Brooke Numerical Systems in 2010. It has been improved in 2012, and the hope is to be able to fully integrate the Clutter Model for comparison with towed array data.

A very useful feature of the Clutter Model formulation is that the computational engine is a subroutine, rather than a standalone program. This facilitates its inclusion in other applications. Work is progressing to include it in the DRDC System Test Bed (a version of which goes to sea with the Canadian Forces). A standalone version with Java GUI and public domain databases [47] was implemented on a Windows system in 2010, and extended to Unix systems in 2011.

Parts of the earlier research had been spun off into a DRDC TIAPS (Towed Integrated Active-Passive Sonar) Technology Demonstrator which has been evaluated in ASW exercises against submarine targets.

Many of the techniques developed under this collaborative project could be useful for the recently approved DRDC Technical Demonstration Project AMASE (Advancing Multistatic Active Sonar Employment).

The 2010 workshop on Validation of Sonar Performance Tools held in Cambridge, UK, had number of scenarios based on the ONR Reverberation Modeling Workshop problems, extended to the complete sonar problem. Support for the sonar modeling validation comes from the Low Frequency Active Sonar program of TNO and the Royal Netherlands Navy.

4.2 Related Projects

The work here 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" was approved for the 2011–2013 Scientific Program of Work at CMRE, but no effort was available for it.

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

This ONR project also contributes to the DRDC Atlantic research program, in particular, Underwater Sensing.

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

5 Publications

This section summarizes some of the PI's main publications during the period 2006–2011.

Journal Publications:

- C. W. Holland and D. D. Ellis. Two modeling approaches for reverberation in a shallow water waveguide where the scattering arises from a sub-bottom interface. *J. Comp. Acoust.*, 17(1):29–43, 2009.
- J. R. Preston and D. D. Ellis. Extracting bottom information from towed-array reverberation data Part I: Measurement methodology. *J. Mar. Syst.*, 78: S359–S371, 2009.
- D. D. Ellis and J. R. Preston. Extracting bottom information from towed-array reverberation data. Part II: Extraction procedure and modelling methodology. *J. Mar. Syst.*, 78:S372–S381, 2009.
- C. W. Holland and D. D. Ellis. Clutter from non-discrete seabed structures. *J. Acoust. Soc. Am.*, 131(6):4442–4449, 2012.
- M. A. Ainslie, D. D. Ellis, and C. H. Harrison. Low frequency bottom reverberation in a Pekeris waveguide with Lambert's rule. *J. Comp. Acoust.* [refereed, submitted]

Conference Proceedings:

- D. D. Ellis. Effect of cardioid and limaçon sensors on towed array reverberation response, *Canadian Acoustics*, 34(3), 102–103, 2006.
- D. D. Ellis, J. R. Preston, P. C. Hines, and V.Young. Bistatic signal excess calculations over variable bottom topography using adiabatic normal modes. In P. L.

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- G. H. Brooke, S. J. Kilistoff, D. J. Thomson, and D. D. Ellis. Performance prediction via the java Acoustic Model Interface. *Canadian Acoustics*, 38(3):64–65, September 2010.
- D. D. Ellis and S. P. Pecknold. Range-dependent reverberation and target echo calculations using the DRDC Atlantic Clutter Model. *Canadian Acoustics*, 38(3):72–73, September 2010.
- D. D. Ellis. Normal Mode and Ray Predictions for the Sonar Performance Assessment Problems, *Proc. Institute of Acoustics*, 32, Pt. 2, 64, 2010. Abstract only.
- D. D. Ellis. Calculations of Reverberation and Fathometer Returns at Short Times, *Proc. Institute of Acoustics*, 32, Pt. 2, 118, 2010. Abstract only.
- D. D. Ellis. Solutions to range-dependent reverberation and sonar workshop problems using an adiabatic normal mode model. In J. S. Papadakis and L. Bjørnø, editors, *4th International Conference and Exhibition on Underwater Acoustic Measurements: Technologies and Results*, pages 485–490, 2011.
- D. D. Ellis and J. R. Preston. DRDC Clutter Model: Range-dependent predictions compared with towed array reverberation and clutter data from the Malta Plateau. In J. S. Papadakis and L. Bjørnø, editors, *4th International Conference and Exhibition on Underwater Acoustic Measurements: Technologies and Results*, pages 657–664, 2011.
- J. R. Preston and D. D. Ellis. A MATLAB and normal mode based adiabatic range-dependent reverberation model. In J. S. Papadakis and L. Bjørnø, editors, *4th International Conference and Exhibition on Underwater Acoustic Measurements: Technologies and Results*, pages 667–674, 2011.

DRDC Reports:

- D. D. Ellis. Normal-mode models OGOPOGO and NOGRP applied to the 2006 ONR Reverberation Modeling Workshop problems. DRDC Atlantic Technical Memorandum TM 2006-289, DRDC Atlantic, Dartmouth, NS, Canada, June 2008. 84 pp.
- J. R. Preston and D. D. Ellis. Report on a normal mode and Matlab based reverberation model. DRDC Atlantic Technical Memorandum TM 2006-290, DRDC Atlantic, Dartmouth, NS, Canada, June 2008. 46 pp.

- J. R. Preston and D. 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. 56 pp.
- T. Kwan and D. D. Ellis. Reverberation calculations over sloping ocean bottoms. DRDC Atlantic Technical Memorandum TM 2009-192, DRDC Atlantic, Dartmouth, NS, Canada, June 2010. 74 pp.
- D. D. Ellis. Calculations of reverberation and fathometer returns at short times using a straight-line ray-path model. DRDC Atlantic Technical Memorandum TM 2011-323, DRDC Atlantic, Dartmouth, NS, Canada, February 2012. 40 pp.

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Each year for 2–3 months the PI was hosted at the Applied Research Laboratory at Penn State University. Special thanks to Dr. David Bradley making it happen, to Kathy Shoemaker for making sure all the details were in place, and to John Preston and Charles Holland for stimulating collaborations during the visits and throughout the year.

The ONR Reverberation Modeling Workshops in 2006 and 2008 were organized by John Perkins, Eric Thorsos and David Knobles. Kevin LePage helped with the problem sets. Mike Ainslie (TNO) organized the Weston Memorial Workshop in 2010 and edited the proceedings.

At DRDC Atlantic, Paul Hines encouraged the development of the Clutter Model, and made contract funds available to Gary Brooke and co-workers. Sean Pecknold did some range-dependent reverberation modeling with a version of Bellhop.

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