Copy No. _____

Defence Research and Development Canada | Recherche et développement pour la défense Canada

DEFENCE R&D DÉFENSE

A Literature Survey of Reverberation Modeling

with Emphasis on Bellhop Compatibility for Operational Applications

Diana McCammon
McCammon Acoustical Consulting

Prepared by:
McCammon Acoustical Consulting
475 Baseline Road
Waterville, NS B0P 1V0

Contract Project Manager: Diana McCammon, 902-538-3003
Contract number: W7707-098272
Scientific Authority: Dr. WA Roger, 902-426-3100 ext. 292

Defence R&D Canada – Atlantic

Contract Report
DRDC Atlantic CR 2010-119
September 2010

Canada

This page intentionally left blank.

A Literature Survey of Reverberation Modeling

with Emphasis on Bellhop Compatibility for Operational Applications

Dr. Diana McCammon
McCammon Acoustical Consulting

Prepared By:
McCammon Acoustical Consulting
475 Baseline Road
Waterville, NS B0P 1V0

Contract Project Manager: Diana McCammon, 902-538-3003
Contract Number: W7707-098272
CSA: Dr. WA Roger, 902-426-3100 ext.292

Defence R&D Canada – Atlantic

Contract Report
DRDC Atlantic CR 2010-119
September 2010

Contract Scientific Authority

Original signed by William Roger

William Roger

Approved by

Original signed by David Hazen

David Hazen

H/TD

Approved for release by

Original signed by Ron Kuwahara for

C. Hyatt

DRP

Abstract

Recent publications of reverberation and scattering strength modeling are reviewed. Emphasis is placed on investigating operationally oriented models (as opposed to research oriented) that may be compatible with the Bellhop propagation model for use within the Environment Modeling Manager (EMM). Special attention is given to the research of Dr. Dale Ellis including his normal mode reverberation model, his clutter model approach, and his scattering strength model. Recommendations are made to consider adding the Ellis normal mode model and the Harrison closed form expressions to the Environment Modeling Manager to compliment Bellhop. It is recommended that a range of bottom scattering strength models be implemented to provide a choice of grazing angle dependences. It is recommended that the Gauss surface scattering strength model be investigated to possibly replace the Ogden-Erskine model. It is also recommended that the Ainslie angle/decay rate relationship be examined to possibly provide the experimental evidence for choosing one scattering strength kernel over another at each operational site.

Résumé

On examine des mémoires récents sur la modélisation de la réverbération et de la force de diffusion. On se concentre sur les modèles à orientation opérationnelle (comparativement à ceux orientés vers la recherche) qui pourraient être compatibles avec le modèle de propagation Bellhop pour utilisation dans l'Environment Modeling Manager (EMM). On a porté une attention particulière aux recherches du D^r Dale Ellis, entre autres à son modèle de la réverbération en mode normal, sa modélisation du fouillis et son modèle de la force de diffusion. On recommande d'examiner l'ajout du modèle de mode normal d'Ellis et des expressions analytiques de Harrison à l'Environment Modeling Manager pour compléter le modèle Bellhop. On recommande de mettre en œuvre divers modèles de la force de diffusion par le fond pour offrir un choix de dépendances sur l'angle rasant. On recommande d'examiner le modèle gaussien de la force de diffusion par la surface comme possibilité de remplacement du modèle d'Ogden-Erskine. On recommande également d'examiner la relation entre l'angle d'Ainslie et le taux de décroissance, ce qui pourrait peut-être justifier expérimentalement le choix d'un noyau de force de diffusion particulier à chaque site opérationnel.

This page intentionally left blank.

Executive summary

A Literature Survey of Reverberation Modeling: with Emphasis on Bellhop Compatibility for Operational Applications

McCammon, D.F.; DRDC Atlantic CR 2010-119; Defence R&D Canada – Atlantic; September 2010.

Introduction: Reverberation can be defined as any projector-related energy received by an acoustic sensor after signal generation onset, that is not energy returned by a target. In the bistatic case, it is also not the one-way received energy associated with the direct blast from the source. This definition excludes ambient/background noise.

Recent publications of reverberation and scattering strength modeling are reviewed. Emphasis is placed on investigating operationally oriented models (trading some accuracy for responsiveness, as opposed to research oriented models having high fidelity but being resource-intensive) that may be compatible with the Bellhop propagation model for use within the Environment Modeling Manager (EMM). Special attention is given to the research of Dr. Dale Ellis including his normal mode reverberation model, his clutter model approach, and his scattering strength model.

Results: Recommendations are made to consider adding the Ellis normal mode model and the Harrison closed form expressions to the EMM to compliment Bellhop. It is recommended that a range of bottom scattering strength models be implemented to provide a choice of grazing angle dependences. It is recommended that the Gauss surface scattering strength model be investigated to possibly replace the Ogden-Erskine model. It is also recommended that the Ainslie angle/decay rate relationship be examined to possibly provide the experimental evidence for choosing one scattering strength kernel over another at each operational site

Significance: The Environment Modeling Manager is a sophisticated tactical oceanography system being developed to aid naval planning and operations. It provides tactical decision aids with accurate and consistent predictions of acoustic conditions and target detectability. This report examines methods to predict reverberation resulting from the use of subsurface projectors, and to recommend how best to enhance EMM to handle target detections during such active sonar operations.

Future plans: It is planned to implement a number of recommendations from this study to enhance the capabilities of the Environment Modeling Manager.

Sommaire

A Literature Survey of Reverberation Modeling: with Emphasis on Bellhop Compatibility for Operational Applications

McCammon, D.F.; DRDC Atlantic CR 2010-119; R & D pour la défense Canada – Atlantique; Septembre 2010.

Introduction : On peut définir la réverbération comme étant toute énergie liée à un projecteur qui est reçue par un capteur acoustique après l'émission d'un signal, et qui n'est pas de l'énergie réfléchie par une cible. En situation bistatique, la réverbération n'est pas l'énergie reçue unidirectionnellement qui est reliée au souffle provenant directement de la source. Cette définition exclut le bruit ambiant.

On examine des mémoires récents sur la modélisation de la réverbération et de la force de diffusion. On se concentre sur les modèles à orientation opérationnelle (en sacrifiant un certain degré d'exactitude pour accroître la réactivité, comparativement aux modèles orientés vers la recherche, lesquels ont une grande fidélité, mais exigent beaucoup de ressources) qui pourraient être compatibles avec le modèle de propagation Bellhop pour utilisation dans l'Environment Modeling Manager (EMM). On a porté une attention particulière aux recherches du D^r Dale Ellis, entre autres à son modèle de la réverbération en mode normal, sa modélisation du fouillis et son modèle de la force de diffusion.

Résultats : On recommande d'examiner l'ajout du modèle de mode normal d'Ellis et des expressions analytiques de Harrison à l'EMM pour compléter le modèle Bellhop. On recommande de mettre en œuvre divers modèles de la force de diffusion par le fond pour offrir un choix de dépendances sur l'angle rasant. On recommande d'examiner le modèle gaussien de la force de diffusion par la surface comme possibilité de remplacement du modèle d'Ogden-Erskine. On recommande également d'examiner la relation entre l'angle d'Ainslie et le taux de décroissance, ce qui pourrait peut-être justifier expérimentalement le choix d'un noyau de force de diffusion particulier à chaque site opérationnel.

Importance : L'Environment Modeling Manager est un système océanographique tactique perfectionné en cours d'élaboration pour aider la planification et les opérations navales. Il fournit des aides à la décision tactique qui font des prévisions exactes et cohérentes des conditions acoustiques et de la détectabilité des cibles. Le présent rapport examine des méthodes de prévision de la réverbération utilisant des projecteurs subsurfaciques, et fait des recommandations sur la meilleure façon d'améliorer l'EMM pour prendre en charge la détection des cibles durant de telles opérations sonar actives.

Perspectives : On prévoit mettre en œuvre certaines des recommandations de la présente étude pour améliorer les capacités de l'Environment Modeling Manager.

Table of contents

List of tables

Acknowledgements

The author gratefully acknowledges the time and assistance from Dr. Dale Ellis in the discussion of his research.

1. Introduction

1.1 Scope of Literature Review

Recent publications of reverberation and scattering strength modeling are reviewed in this paper. In 2004, McCammon [1] described all the current models and components of active sonar modeling with emphasis on the creation of sonar stimulators. The emphasis in this paper is placed on investigating operationally oriented models (trading some accuracy for responsiveness, as opposed to research oriented models having high fidelity but being resource-intensive) that may be compatible with the Bellhop propagation model called BellhopDRDC for use within the Environment Modeling Manager (EMM). Special attention will also be given to the research of Dr. Dale Ellis including his normal mode reverberation model, his clutter model approach and his scattering strength model.

Section 2 will discuss newer approaches for computing Reverberation. Section 3 will discuss Scattering Strength models. Section 4 contains a summary and recommendations.

1.2 Definition of Reverberation

A general definition of reverberation is any source-related energy received by an acoustic sensor after signal generation onset that is not energy returned by a target, and in the bistatic case, not the one-way received energy associated with a direct blast from the source. This definition excludes ambient/background noise. A generalized equation for the bistatic reverberation intensity due to boundary scattering can be written as:

$$R(t) = \iint_{A(t)} I_0 \sum_{p} \sum_{q} P_p \, P_q \, S(\theta_p, \theta_q, \varphi) \, dA \qquad (1)$$

Where, the subscripts p and q refer to source and receiver ray fans and φ represents the bearing angle to the scattering point. I_0 is the intensity of the source of pulse length τ, dA is the elemental scattering area, a function of range and pulse length that is connected by the propagation terms P. The scattering strength S is a function of the angles each ray from source and receiver makes with the scattering surface, as well as the azimuthal angle. The double sum counts all rays (or modes) associated with each propagation expression P. The double integral covers all areas touched by the pulse at time t. These areas are bounded by ellipses whose size and shape are determined by the geometry, pulse length and ray angles. All angles have implicit time dependence because they have different path lengths in the water column, and the angles at source and receiver θ_{p0} and θ_{q0} are not the same as the angles at the scattering surface (θ_p and θ_q) due to water column refraction. In this most general expression, the scattering strength equation can be a complicated function of angles and slopes of the scattering surface. All of the high fidelity reverberation models follow this mathematics; however, each model chooses different methods for evaluating the propagation field, the scattering function and in some cases, the scattering area.

Some of the older models of reverberation are the Generic Sonar Model (GSM), Cass/Grab, BiRasp, and ASTRAL. A more complete listing of reverberation and active performance models is given by Etter [2]. Traditionally, reverberation has been computed using ray theory because the travel time of the rays was a readily calculated quantity, whereas with the Parabolic Equation (PE) or Normal Mode theory, it was not. However, some researchers have constructed normal mode reverberation models, one of which will be described in Section 2.1.

Beam patterns are an important part of the reverberation calculation, but three-dimensional patterns such as the conical beams from a towed array can be cumbersome and time consuming in a reverberation calculation. Ellis [3] has suggested an effective beam pattern approach that would be good for reverberation with flat bottom monostatic geometry. This approach was extended by Theriault [4]

There has been some research into building reverberation from the parabolic equation approach. In particular, Tappert [5] and Tappert and Ryan [6] have put forward a three dimensional model for long range oceanic boundary reverberation. These models are high fidelity and generally suitable for research but not operational use. There would be no ability to combine Bellhop with any of these PE models.

2. Reverberation Research

2.1 Normal Mode Reverberation

The research of Dr. Dale Ellis has centered on the creation of a normal mode reverberation model suitable for shallow water low frequency analysis. He has concentrated on a normal mode approach because modes have been quite successful in modeling shallow-water transmission loss. In [7], his method is outlined. He obtains the travel time for each mode from its group velocity and the arrival angle at the bottom interface from its phase velocity. His choice of mode functions allows him to decompose the mode amplitudes into up-going and down-going waves to obtain the incident and reflected field at the surface and bottom. A plane wave scattering function such as Lambert's Law can then be applied. In [8], Ellis demonstrates the quality of this modeling approach by comparisons with bistatic towed-array reverberation measurements in the Mediterranean in a flat-bottomed area. He shows that shallow-water reverberation has a strong dependence on propagation conditions, especially bottom loss.

In [9], Ellis, Deveau, and Theriault extend the calculations from surface and bottom reverberation to include volume reverberation, target echo and signal excess. In this paper the authors note that, in general, the range dependence of the signal excess will likely be quite sensitive to the details of the propagation loss.

Normal mode theory is naturally suited to shallow-water low-frequency calculations because the number of modes is small leading to very fast calculations. However it is usually restricted to range independent environments. In [10], Ellis, Preston, Hines and Young extend the method to include a limited range dependence using adiabatic normal modes. In [11], Kwan and Ellis study reverberation over a sloping bottom using adiabatic normal modes. For this research, combinations of computer languages are used. The adiabatic normal mode coefficients, eigenvalues, and group velocities are computed using the Fortran code PROLOS. These are input to a Matlab routine to compute reverberation and display results. The results are compared to the Harrison energy-flux (see section 2.3.1) predictions, a range-dependent reverberation case from the Reverberation Modelling Workshop and also with the predictions of the DRDC SWAMI (Shallow Water Active-sonar Modelling Initiative) model. The comparisons with the energy-flux methods are very good, except near mode cut off at long ranges.

In recent years, Dr. Ellis has studied modeling the reverberation in other ways. His more exact method described above involves using the group velocity of each mode to provide the time dispersal of the propagated acoustic field. A quicker method (akin to the energy flux method first proposed by Weston [12] for propagation) can provide a depth averaged reverberation field with a simple linear decay with time suitable for monostatic backscattering. Dr Ellis feels that the advantages in speed of the energy flux approach more than outweigh the cost in accuracy, although the temporal details may be required for target echo modeling.

The techniques used in all of these modeling efforts are not applicable to Bellhop because they are designed specifically to take advantage of the normal mode decomposition. However, EMM could certainly employ the normal mode reverberation model in addition to Bellhop. There could be logic defined to select which model is best suited for the environment in question, in terms of both speed of execution and accuracy requirements. The normal mode approach would be only weakly range dependent.

2.2 DMOS – Bellhop Extension

In 2006, Calnan [13] reported on the inclusion of Bellhop into the DRDC Atlantic Model Operating System (*DMOS*) along with the normal mode model PMODES. DMOS is an evolution of the *SWAMI* suite of programs in use at DRDC Atlantic that enables a user to produce modelled reverberation, transmission loss, signal excess, and probability of detection for an active sonar. In order to make the choice between the two propagation engines (Bellhop and PMODES) smooth and seamless, Calnan created several 'translation' programs to create the input files, rename the output files and convert the Bellhop arrival salt tables into eigenray files. As of 2006, the version of Bellhop in DMOS was 2005's BellhopDRDC_S and DMOS did not handle bistatic scenarios.

2.3 New Directions in Research

Two opposing philosophies for computing reverberation have recently been put forward. In 2003, C. Harrison proposed some closed form solutions for reverberation and signal excess that produce a diffuse reverberant field. This method is fast and operationally attractive, effectively averaging the field in range and frequency. In 2004, B. Cole proposed a modified coherent reverberation model to produce Lloyd's Mirror type oscillations in the reverberation time series. These two approaches are discussed below.

2.3.1 Closed Form Expressions for Reverberation and Signal Excess

In 2003, C.H. Harrison [14] published his derivations of closed form solutions for propagation and diffuse reverberation at high and low frequencies and in isovelocity but arbitrary range-dependent environments with three different choices for scattering strength laws. As this is an analytical approach, it is restricted to simple profiles; however, these solutions are quite tractable, and in the context of broadband active sonar where single frequency effects are smoothed out, these formulas explain the trends quite well. In [15], Ainslie extended the solution set by including general separable scattering coefficients with an arbitrary power law dependence. In [16], Harrison has shown a simple relationship between range and frequency averages for broadband sonar.

The following expression is an example of Harrison's solution for bottom reverberation using Lambert's law (see section 3.1.1) for a range independent case at high frequency:

$$R_b = \frac{\mu \Phi p}{\alpha^2 r^3} \left\{ 1 - \exp(-W_{RI}^2) \right\}^2 \qquad (2)$$

Where, μ is the Lambert coefficient, Φ is the beamwidth, p is the pulse length, α is the bottom attenuation, r is the range, θ_c is the critical angle, H is the water depth, and $W_{RI}^2 = \alpha r \theta_c^2 / 2H$.

With Eq. (2) at short range, $1 - \exp(W_{RI}^2) \to W_{RI}^2$ so that the reverberation has a range dependence of 1/*r*, while at long range, $1 - \exp(W_{RI}^2) \to 1$ so that the reverberation has a range dependence of $1/\alpha^2 r^3$. In the long range region, the bottom attenuation affects the slope of the range decay, while it does not appear in the short range region. (This bottom attenuation dependence in the decay rate was noticed and utilized by Ellis and Preston [17] when they were inverting reverberation data to obtain bottom properties.) The transitional bend in the reverberation occurs at about $W_{RI}^2 = 1$, which, according to Harrison, is about 2 km for typical values of ocean bottoms in 100 m of water.

In 2005, Harrison [18] extended his closed form solutions to include the bistatic case with variable bathymetry and sound speed. In this case, the formulations are more complicated but still intuitive. He finds that refraction does have an important effect on reverberation and SRR (signal-to-reverberation ratio).

Harrison argues that for operational research studies and trial planning, more model sophistication is hardly necessary. He feels these closed form solutions can provide useful benchmarks for testing other models, and Kevin LePage [19] has used them while testing the R-Snap model.

A good research topic for Bellhop evaluation would be to compare these solutions with a Bellhop generated SRR to ensure that the correct trends with range, bottom loss, pulse length, scattering strength, frequency and beamwidth are being followed. Further comparisons with Bellhop in more rigorous environments with refracting sound speed profiles should prove very interesting. Particular attention should be paid to the products of these two approaches when using range smoothing on Bellhop's output.

2.3.2 Coherent Bottom Reverberation

The appearance of coherent temporal structures in reverberation measured by hull-mounted and other near-surface sonars has been noted using both Linear Frequency Modulation (LFM) and Continuous Wave (CW) pulses. The coherent effects produce distinct patterns in the reverberation time series analogous to the Lloyd mirror effect in propagation loss as a function of range. In 2004, Cole et al [20] published a model for coherent bottom reverberation and compared it to at-sea measurements. They show Lloyd's mirror interference patterns in temporal records taken in the Persian Gulf. The critical requirement for this pattern to form is that the pulse length is long enough to include the interfering paths but not so long that several cycles of the pattern can interfere.

In the model presented by Cole, in order to avoid the sometimes spurious behaviour of a completely coherent formulation, the authors restrict the interfering paths to just the first four paths scattered from the bottom. (source-bottom-source, source-surface-bottom-source, source-bottom-surface-source, and source-surface-bottom-surface-source). This is a form of limited coherence which lets only the contributions from a small portion of the classical pulse length projected area to add together coherently. It assumes the bottom loss on scattering is much greater than the surface scattered loss, and it assumes short narrowband pulses are being transmitted. The requirement for coherence is that two or more arrivals overlap in time with phases that add together or cancel effectively. Taking just the direct and surface reflected paths as an example, if the pulse length is shorter than the time difference between the two paths then there can be no overlap in time of arrivals and all paths would add incoherently. If the pulse length is greater than the time difference between the paths, then the two paths can overlap and add constructively and destructively. If, however, the pulse length is very much greater, so that many paths are combining, then the interference pattern is smeared and the reverberation approaches the incoherent behaviour. Thus the presence of coherence is very dependent on the pulse length and bandwidth, the physical geometry of the scenario, and the amount of surface scattering loss (which destroys Lloyd's mirror). Cole states "… the effect could be widely prevalent in many reverberation data sets but is not recognized due to it being obscured by the long pulse length and/or wide bandwidth pulses generally transmitted."

When these patterns occur in reverberation, then they can potentially also occur in the target echo time series, albeit at different times than the reverberation time series. This would lead to a signal excess graph with many potential oscillations with range.

One of the interesting characteristics of coherent reverberation is that the fluctuation statistics will not be the same as incoherent (diffuse) reverberation. In particular, the false-alarm rate (Pfa) will be higher than Rayleigh because of the deterministic structures that appear in the time series realizations, equivalent to successive pings. Because of this effect on the false-alarm rate it would be very advantageous operationally to determine just exactly what environmental conditions must be present to produce the coherence and just what the Pfa statistics will be.

Cole notes that he has been told that later versions of the CASS model of Weinberg and Keenan [21] will be modified to include this capability of computing coherent reverberation. Modeling this coherent interference using the four strongest paths will not be difficult for BellhopDRDC because the CASS and BellhopDRDC models use similar approaches.

2.3.3 Philosophical questions for operational models

In the last two sections, two very different approaches for modelling reverberation have been presented. The energy flux approach provides fast closed form solutions that model smooth diffuse reverberation, simple target echoes, and simplified signal excess. The modified coherent approach requires careful combinations of the four major propagation paths with time to provide path overlap necessary for coherent additions to take place.

The philosophical questions that must be decided before improving models for operational usage are these: Should the operational models be *increased* or *decreased* in complexity? Will the environment ever be known sufficiently accurately to correctly predict any coherence structures? Should operational models become more complicated and time consuming in order to capture all possible reverberation nuances? Are there short cuts that could be developed to mitigate potential coherence effects without having to compute them, such as using a worst-case Pfa curve whenever there is a potential for coherence effects, rather than trying to predict the actual SE and Pfa?

2.4 Applications using Reverberation Modeling

2.4.1 Bottom Loss and Scattering Strength Estimation

In [22] and [17] Drs Ellis and Preston used a ray-based reverberation model from GSM (Generic Sonar Model) in the inversion of measured reverberation to estimate the bottom scattering strength, and bottom loss (and the geoacoustic properties from the bottom loss). They found that the bottom loss controlled the rate of temporal decay of the reverberation while the scattering strength influenced the overall level of the reverberation. They also found that the critical angle and bottom loss at normal incidence were the most useful bottom parameters in establishing the decay rate. The inversion method they used at first was manual matching, checking the fit at different frequencies and beams and qualitatively estimating the goodness-of-fit. In other publications, Preston employed an automated method called simulated annealing [23]. It was concluded that at-sea inversions were reasonably successful and that the method was worth refining. Preston and Ellis state that the method is clearly not a precise tool; however, it does provide an area average that is ideally suited for an REA (Rapid Environmental Assessment) survey. For computational efficiency, they assumed a range-independent environment, monostatic calculations, and broadband beam patterns.

Note that Holland [24] and [25] has determined that inverting reverberation for seabed parameters may have an uncertainty as large as several 10's of dBs, due to uncertainty in the angular dependence of the scattering kernel. He suggests modifying the inversion by including independent measurements of backscattering from the critical angle to as low an angle as practical. He also suggests conducting the reverberation measurements in isovelocity or upward refracting environments, and he advocates using multiple source/receiver depths. A measurement technique for bottom scattering is suggested by Holland et al in 2000 [26].

In 2007, Ainslie [15] published a study of the bottom parameters that could be inferred from multipath bottom reverberation in shallow water. Assuming a power law dependence of the backscattering strength on grazing angle, he determined that the angle dependence of the scattering strength could be inferred from the decay rate of long range reverberation in isovelocity water. This would help greatly to mitigate the bias errors reported by Holland when the wrong scattering kernel's grazing angle dependence is used. Ainslie also suggests reverberation inversions be made using multiple measurements at different depths, frequencies and/or different sound speed profiles. This paper presents a potentially useful technique (here called angle/decay rate analysis) to determine which angle dependence to select in modeling bottom scattering strength.

This use of a reverberation model to provide bottom information by inversion could also be accomplished using a Bellhop reverberation calculation, and in addition, because of the capabilities of Bellhop's reverberation model, range-dependent and bistatic geometries could be used. Bellhop's reverberation model contains a choice of scattering strength angle dependences which will allow the use of Ainslie's angle/decay rate analysis to choose the correct angle dependence.

2.4.2 Clutter Model

In [10], Ellis, Preston, Hines and Young have designed a clutter model suitable for large scale bottom irregularities which uses a basic flat-bottom model and varies the Lambert scattering strength coefficient over the area to achieve isolated increases in reverberation. This deterministic clutter model can be used to define known reverberant areas on the bottom (such as ship wrecks or isolated sea mounts) which could then be subtracted from a measured reverberation to 'clean up' noisy data. This deterministic clutter definition could also be accomplished in a Bellhop reverberation calculation by inputting a range-dependent (down range and cross range) Lambert coefficient array.

3. Scattering Strength

3.1 Bottom Scattering Strength Models, Old and New

3.1.1 Lambert's Rule

Lambert's Rule (also referred to as Lambert's Law) is a very simplified way of describing sound scattering from the sea floor. It assumes the sound is scattered equally in all azimuthal directions, that is, diffusely rather than specularly. The scattering strength is defined as a function of the incident grazing angle θ_{in}, the reflected grazing angle θ_{out}, and a magnitude called the Lambert coefficient μ. Mackenzie who was the first acoustician to study this rule, fitted the coefficient to experimental data and obtained μ=0.002 or -27 dB, hence, this value is often called the Mackenzie coefficient. The equation for scattering strength under Lambert's Rule is given by

$$S_{Lambert} = 10\log(\mu \sin\theta_{in} \sin\theta_{out}) \tag{3}$$

This formulation is not a rigorous theoretical result; it is viewed by most acousticians as a simple geometrical argument but it has the virtue of fitting the angle dependence of a lot of observed bottom scattering data at moderate grazing angles in the 20º to 60º range.

Harrison [14] notes that scattering laws are poorly known and to date there is no database of scattering strength. Because of the relative simplicity of Lambert's Rule, many researchers have criticized its use, citing its lack of frequency dependence and lack of relationship to sediment properties of roughness, density, penetrability, etc. Preston defends the use of Lambert's Rule by pointing out that the coefficient can be defined to be dependent on frequency, sediment content and roughness. In the extraction of bottom properties from the inversion of reverberation measurements, Preston and Ellis in [22] and [17] found values of the coefficient that ranged from -27 dB to -35 dB.

3.1.2 Omni-directional Rule (Lommel-Seeliger Law)

The general form of omni-directional scattering is dependent only on the incident grazing angle.

$$S_{omni} = 10\log(\mu_o \sin\theta_{in}) \tag{4}$$

Here, the coefficient μ_o can be dependent upon the surface material properties and possible frequency, just as the Lambert's Rule coefficient.

This theory features a first power dependence on the sine of the grazing angle, so in monostatic backscattering cases, it falls off more slowly with grazing angle than does Lambert's Rule. McCammon [27] fitted an omni-directional coefficient to older published data of monostatic backscattering and was able to tie the value of the coefficient to the bottom properties. Table 1 shows these empirical relationships.

Table 1: Empirical relationships between omni coefficients and sediment properties or descriptions from McCammon[27].

Omni coefficient μ_o (dB)	Sediment Description	Sediment Density	MGS Province
18.7	Rock, coarse sand, shell	Greater than 2.2	7-9
27.5	Fine sand, silt	1.7-2.2	1-4
33.5	Clay, mud	Less than 1.7	5-6

3.1.3 Ellis and Crowe 3-D Scattering function

To improve on Lambert's Rule at high grazing angles where the difference between scattering and reflection from the fathometer returns starts to blur, in 1991 Ellis and Crowe [28] developed a facet term to express the high angle reflectivity from facet-like planes. This term is important for reverberation near the fathometer returns or in the bistatic case near the direct blast (forward scattering near the specular arrivals). The Ellis and Crowe facet term requires two coefficients: υ is the facet strength and σ is the facet width or RMS slope assuming a Gaussian random surface. Values for these two coefficients are suggested to be facet width σ=10º (but expressed in radians) and facet strength $\upsilon = \Re$, the sea floor reflection loss at normal incidence, in other words the normal bottom loss. The general expression for this 3-D scattering function is

$$S(\theta_{in}, \theta_{out}, \phi) = \mu \sin\theta_{in} \sin\theta_{out} + \upsilon(1+\Omega)^2 \exp(-\Omega / 2\sigma^2) \tag{5}$$

where the incident and scattered angles are labelled θ_{in} and θ_{out}, and the bistatic angle of the receiver from the specularly reflected direction is ϕ. The symbol Ω is a measure of the deflection of the scattered ray from the specularly reflected ray.

$$\Omega = \left(\cos^2\theta_{in} + \cos^2\theta_{out} - 2\cos\theta_{in}\cos\theta_{out}\cos\phi\right) \Big/ (\sin\theta_{in} + \sin\theta_{out})^2 .$$

For backscattering, this term Ω simplifies to $\cot^2\theta_{in}$.

The value of this scattering function is its geometric generality, making it useful for bistatic applications. The facet portion of this function could also be applied to the omni-directional scattering rule rather than Lambert's Rule if required.

3.1.4 ONR Workshops Bottom Scattering Strength Models

For the ONR sponsored reverberation workshops held in November 2006 and in May 2008, the bottom scattering strength [29] was specified for all participants. It was based on the perturbation theory for backscatter at frequencies no higher than 3.5 kHz. A critical input to this theory is the roughness spectra of the surficial layer of the bottom and the theory predicts the grazing angle dependence to be $\sin^4\theta$. This is a very steep fall off at low grazing angles, as compared to Lambert ($\sin^2\theta$) or omni ($\sin\theta$), and because of this, the perturbation theory is often coupled with sub-bottom scattering and/or fish models which will contribute at shallow angles. At this workshop, for coherent forward scatter, the small slopes approximation to the Kirchhoff approximation was specified. For smooth sand bottoms, the lowest order term was used while for rougher bottoms, the second order term was included. The document in [29] specifies all the equations for 2-D and 3-D reverberation problems that were studied at these workshops.

For operational use, these models are not suitable because they require a detailed knowledge of the surficial roughness of the bottom.

3.2 Surface Scattering Strength

3.2.1 Ogden-Erskine

In 1992, Ogden and Erskine [30] produced a set of empirically derived equations to predict scattering strength from 50 to 1000 Hz, although it is often used at higher frequencies. An attempt to extend these expressions to the bistatic case was made by Vendetti [31] in 1993. Improvements to this theory are given in Nicholas, Ogden and Erskine [32] in 1998. The basic theory contains two parts, depending on the wind speed. The low wind speed portion was fitted empirically by Ogden and Erskine while the high wind speed portion comes from the empirical curves of Chapman-Harris. Linear interpolation in dB space is used to obtain the scattering strength in wind speed regions between these two curves.

3.2.2 McDaniel

In 1993 McDaniel [33] published a good review of theories and data relating to sea surface reverberation between 3 kHz and 60 kHz. She champions the use of Composite Roughness theory for modelling the surface scattering, combined with a bubble scattering term. She states that high grazing angle scattering is due to the rough ocean surface while low grazing angle scattering comes from resonant sub-surface microbubbles. The major input for this model is the sea surface spectrum of waveheights.

3.2.3 Gilbert Bubble Model

The Gilbert [34] model published in 1993 is a treatment of the contribution from the clouds of subsurface bubbles that enhance low-angle scattering. To match the data, an empirically derived relation between wind speed and sound speed fluctuations is obtained by visually matching the Ogden-Erskine model. The values obtained from this theory are similar to those of the Ogden-Erskine model in the region of the Chapman-Harris (high winds) but the advantage of the Gilbert theory is that the bistatic angular dependence may be more geometrically accurate. This model can be coupled with a composite roughness model in the same way as McDaniel's model for low wind speeds.

3.2.4 3-D Broadband Bistatic Surface Scattering Model

In 2000, Gauss, Fialkowski, Wurmser and Nero [35] published a model for the low frequency region from 50 to 1000 Hz and for the mid frequency region 1 to 10 kHz of operational active sonars. This is a semi-empirical model that includes contributions from the air-sea interface using both small slope approximations and perturbation theory for swell contributions. The sub-surface bubble cloud is modeled with an improved form of the Gilbert Bubble model. This model is physics-based and multistatic; however, it contains four parameters that were matched to data, making it actually a combination of empirical and physical. The authors note that they feel their model should be viewed as an interim model as they are still refining some of the empirical relationships.

The model they have presented shows that bubbles become increasingly important with both increasing frequency and wind speed and with decreasing grazing angle.

3.2.5 ONR Workshops Surface Scattering Strength Model

For the ONR sponsored reverberation workshops held in November 2006 and in May 2008, the surface scattering strength [29] was specified for all participants. The surface backscattering model was based on first order perturbation theory using the isotropic Pierson-Moskowitz spectrum for a fully developed sea. The forward scattering model was the Kirchhoff approximation, keeping one or two terms according to the roughness of the surface. No bubble models were defined.

3.3 Volume and Sub Bottom Scattering

3.3.1 Fish

In 2000, Gauss, Fialkowski, Wurmser and Nero [35] also published a fish scattering strength. This model requires the density of fish, the mean size of their swim bladders, and the layer depths in which they are lying. The authors note that near-surface fish can be a significant and complex low- and mid-frequency scattering mechanism and that the fish, and not the bubbles, may in fact be responsible for reported low-frequency surface scattering strengths at low grazing angles being elevated over rough-surface scattering predictions in low and moderate sea states.

In 1993, Love [36] also published a fish scattering strength model that has virtually the same inputs as the Gauss model. Love found good comparisons with data when the knowledge of the biological life was well known. He obtained his biological inputs from fishery surveys on the number and sizes of fish populations in the area. His data shows a swim bladder resonance for blue whiting at about 1000 Hz when lying at 80 m, and 2000 Hz when lying at around 400 m depth. His major conclusion was that “the extent of knowledge required for accurate predictions at frequencies near or below [the swim bladder] resonance is significantly greater than at frequencies well above resonance, where scattering strengths are relatively insensitive to parameters other than fish density.’

Both of these models require a detailed knowledge of the type, size and location of fish for accurate predictions of volume scattering strength, and therefore are not very operationally useful. In Love’s paper, he tries to use fishery surveys to supply the needed information but he notes that species of no commercial value are dismissed as unimportant in the fishery sense, although they could be major contributors to volume reverberation at low frequencies (below 5000 Hz). Thus, these surveys may not be very useful for operational acoustic prediction purposes.

3.3.2 Sub-surface bottom volume scattering

Holland [37] proposes a model for interface scattering, sub-bottom sediment volume scattering, and a sub-bottom horizons component. His model is proposed for the frequency region 100 - 1000 Hz. It requires inputs of bottom properties including sediment thicknesses, sound-speed profile and attenuation. It predicts that the low angle data are controlled by sediment volume inhomogeneities while the intermediate angle data are controlled by the rough basement horizon.

Li, Tang and Frisk [38] have evaluated several sound propagation models used in bottom volume scattering studies including Hines [39], and Ivakin [40]. They discuss the validity of using the equivalent of surficial scattering strength to characterize the sediment volume scattering process. They conclude that because of multipath contribution within the sediment volume, the results will be sensitive to the layer thickness no matter what type of sediment is found below the surface.

Thus, to apply any of these volume scattering models, a detailed knowledge of the sediment structure and composition would be required, knowledge that would probably not be available for an operational model.

4. Summary and Recommendations

In this brief survey of reverberation and scattering strength models, the emphasis has been on examining models that can be implemented by or combined with the BellhopDRDC propagation prediction model for operational applications controlled by the EMM.

D. Ellis has put considerable effort into using normal mode theory to compute reverberation and has created several models along these lines. While his models are not useable by the ray model BellhopDRDC, they can be a compliment to a Bellhop reverberation model. That is, the normal mode approach is naturally suited to making low frequency shallow water predictions, where Bellhop would be less accurate and less efficient. Therefore, consideration should be given to including both approaches and using logic within EMM to choose which one to employ.

C. Harrison has developed a new approach to diffuse reverberation modeling with the derivation of closed form expressions for reverberation, target echo and signal excess. These expressions do include range dependence, sound speed profiles, and bistatic applications, and they are tractable for fast operational use. It is recommended that a BellhopDRDC reverberation model be tested against these solutions for accuracy and runtime. The result of these tests may provide a clear set of criteria for choosing between the two models within EMM.

B. Cole et al. have determined that coherent reverberation can often be found under conditions of smooth seas, surface mounted sonars and short pulse lengths. Their approach to predicting this coherent reverberation is readily implementable by a BellhopDRDC reverberation model; however, the question is whether it *should* be implemented. This is a philosophical question: should operational models become more complicated and time consuming in order to capture all possible reverberation nuances or should they always strive for average general behaviour like that predicted by the diffuse reverberation closed form solutions.

A short review of applications for reverberation models include bottom loss and scattering strength inversions and clutter models. Both of these applications are suitable for a BellopDRDC reverberation model.

Scattering strength models are discussed. For bottom scattering strength there are no new candidates. The BellhopDRDC reverberation model should include the omni rule, Lambert's rule and the Ellis and Crowe 3-D model. The Ainslie angle/decay rate relationship may provide a tool for EMM to choose which model to use. The models in the ONR reverberation workshops are not suitable for operational use because they require hard-to-find inputs such as the bottom surficial roughness spectrum.

For surface scattering, the newest model is the 3-D broadband model from Gauss et al. It contains scattering models for the air-water interface, bubble clouds and fish. It is recommended that the first two terms of this model (not the fish) be investigated more fully for possible inclusion in BellhopDRDC surface reverberation.

For volume and sub-bottom scattering, none of the models investigated are suitable for operational use. The models are not proven over a wide variety of conditions and the inputs are not easily obtainable.

To summarize the recommendations arising from this literature survey with regard to BellhopDRDC reverberation modelling within the EMM:

- Consider adding the Ellis Normal Mode Reverberation model to the suite in EMM as an alternative choice to BellhopDRDC, specifically for low frequency, shallow water situations.
- Test the Harrison closed-form expressions for diffuse reverberation and signal excess against BellhopDRDC reverberation for accuracy and run time. If the tests are favourable, consider adding these expressions to EMM as an alternative choice to BellhopDRDC.
- Examine the change to the probability of false alarm (pfa) rate when in coherent reverberant areas. Investigate the possibility of defining a rule for choosing Pfa statistics given pulse length, wind speed, and location of receivers.
- Consider implementing a clutter model by extending the Lambert coefficient input to permit an array of area dependent designated values.
- Implement a choice of bottom scattering strength models with different grazing angle dependences.
- Investigate the use of the Ainslie angle/decay rate relationship to determine which bottom scattering strength angle dependence to choose (possibly for in situ application by the EMM to measured reverberation or in a scattering strength database).
- Investigate the 3-D broadband surface scattering model of Gauss et al. Determine if all the inputs have been clearly defined and if this model is better (bistatic and broadband) than the Ogden-Erskine model.

References

[1] Diana McCammon, “Active Sonar Modelling with emphasis on sonar stimulators”, DRDC Atlantic Contract Report CR 2004-130, DRDC Atlantic, Dartmouth, NS, Canada, (2004).

[2] P.C. Etter, “Recent advances in underwater acoustic modelling and simulation”, Journal of Sound and Vibration **240**(2), 351-383, (2001)

[3] Dale D. Ellis, Effective vertical beam patterns for ocean acoustic reverberation calculations”, IEEE J. Oceanic Engineering, **16**(2), 208-211, (1991).

[4] J.A. Theriault, "Modelling azimuthal and vertical directionality of active sonar systems for undersea reverberation", Canadian Acoustics, **20**(3), pp73-74, (1992)

[5] F. Tappert, “Full-wave three-dimensional modeling of long-range oceanic boundary reverberation”, J. Acoust. Soc. Am., **88** s84, (1990)

[6] F. Tappert and F. Ryan, “Full-wave bottom reverberation modeling”, J. Acoust. Soc. Am., **86** s65, (1989)

[7] Dale D. Ellis, “A shallow-water normal-mode reverberation model”, J. Acoust. Soc. Am., **97**(5), 2804-2814, (1995).

[8] Dale D. Ellis, “Shallow water reverberation: Normal-mode model predictions compared with bistatic towed-array measurements”, IEEE Journal of Oceanic Engineering, Special issue on Sonar System Technology, Vol. **18**(4), 474-482, (October 1993).

[9] Dale D. Ellis, Terry J. Deveau, and James A. Theriault, “Volume reverberation and target echo calculations using normal modes” in *Oceans ’97 MTS/IEEE Conference Proceedings* (IEEE, Piscataway, NY, USA) Vol. **1**, 608-611, (October 1997).

[10] Dale D. Ellis, John R. Preston, Paul C. Hines, and Victor W. Young, “Bistatic signal excess calculations over variable bottom topography using adiabatic normal modes” in *International Symposium on Underwater Reverberation and Clutter*, P.L. Nielsen, C.H. Harrison and J.C. LeGac, eds., NATO Undersea Research Center, La Spezia, Italy, pp. 97-104, (2008).

[11] Tony Kwan and Dale D. Ellis, “Reverberation Calculations over Sloping Ocean Bottoms”, DRDC Atlantic Technical Memorandum TM 2009-192, DRDC Atlantic, Dartmouth, NS, Canada, (2009).

[12] D.E. Weston, “Acoustic flux methods for oceanic guided waves”, J. Acoust. Soc. Am., **68**(1), 287-296, (1980).

[13] C. Calnan, “DMOS – Bellhop Extension”, DRDC Atlantic Contract Report CR 2006-005, DRDC Atlantic, Dartmouth, NS, Canada, (2006).

[14] C.H. Harrison, "Closed-form expressions for ocean reverberation and signal excess with mode stripping and Lambert's law", J. Acoust. Soc. Am., **114**(5), 2744-2756, (2003).

[15] Michael A. Ainslie, "Observable parameters from multipath bottom reverberation in shallow water", J. Acoust. Soc. Am., 121(6), 3363-3376, (2007).

[16] C.H. Harrison and J.A. Harrison, "A simple relationship between frequency and range averages for broadband sonar", J. Acoust. Soc. Am., **97**(2), 1314-1317, (1995).

[17] Dale D. Ellis and John R. Preston, "Extracting bottom information from towed-array reverberation data Part II: Extraction procedure and modeling methodology", J. Marine Systems, **78**, S372-S381, (2009).

[18] C.H. Harrison, "Closed form bistatic reverberation and target echoes with variable bathymetry and sound speed", IEEE Journal of Oceanic Engineering, **30**(4),660-675, (2005)

[19] K. LePage, "Monostatic reverberation in range dependent waveguides: the R-Snap model", SACLANT Undersea Research Center, La Spezia, Italy, Report SR-363, (2002).

[20] Bernard Cole, James Davis, William Leen, William Powers and John Hanrahan, "Coherent bottom reverberation: modeling and comparisons with at-sea measurements", J. Acoust. Soc. Am., 116(4), 1985-1994, (2004).

[21] R. Keenan, "An introduction to GRAB eigenrays and CASS reverberation and signal excess", *Proceedings of the MTS/OCEANS 2000 Conference*, **2**, 1065-1070, (2000)

[22] John R. Preston and Dale D. Ellis, "Extracting bottom information from towed-array reverberation data Part I: Measurement methodology", J. Marine Systems. **78**, S359-S371, (2009).

[23] J. R. Preston, "Shallow Water Ocean Reverberation Data Analysis and Extraction of Seafloor Geo-acoustic Parameters below 4kHz," Ph.D. Thesis, The Pennsylvania State University, State College, PA, (August 2002).

[24] Charles W. Holland, "Fitting data, but poor predictions: Reverberation prediction uncertainty when seabed parameters are derived from reverberation measurements", J. Acoust. Soc. Am., **123**(5), 2553-2562, (2008)

[25] Charles Holland, "On errors in estimating seabed scattering strength from long-range reverberation (L)", J. Acoust. Soc. Am.,118(5), 2787-2790, (2005)

[26] Charles W. Holland, Reginald Hollett and Luigi Troiano, "Measurement technique for bottom scattering in shallow water", J. Acoust. Soc. Am., 108(3), 997-1011, (2000)

[27] Personal communication.

[28] Dale D. Ellis, and D.V. Crowe, "Bistatic Reverberation Calculations Using a Three-dimensional Scattering Function", J. Acoust. Soc. Am., **89**, 2207-2214 (1991).

[29] The scattering models are given in Scattering_models5.doc found at ftp://ftp.ccs.nrl.navy.mil/pub/ram/RevModWkshp_II/Workshop_I_Problem_definitions.

[30] Peter M. Ogden and Fred Erskine, “An empirical prediction algorithm for low-frequency acoustic surface scattering strengths”, Naval Research Lab, NRL/FR/5160-92-9377, (April 28, 1992)

[31] A. Vendetti, “An interim extension of the Ogden-Erskine empirical prediction for low-frequency acoustic surface scattering strengths”, Naval Air Warfare Center, Code 5044, TN-5044-150593, (May 15, 1993)

[32] Michael Nicholas, Peter Ogden and Fred Erskine, “Improved empirical descriptions for acoustic surface backscatter in the ocean”, IEEE Journal of Oceanic Engineering, **23**(2), 81-95, (1998)

[33] Suzanne T. McDaniel, “Sea surface reverberation: a review”, J. Acoust. Soc. Am., **94**(4), 1905-1922, (1993)

[34] Kenneth E. Gilbert, “A stochastic model for scattering from the near surface oceanic bubble layer”, J. Acoust. Soc. Am., **94**(6), 3325-3334, (1993)

[35] Roger Gauss, Joseph Fialkowski, Daniel Wurmser, and Redwood Nero, “New broadband models for predicting bistatic surface and volume scattering strengths”, *ONR Environmentally Adaptive Sonar Technology (EAST) Peer Review*, (8-11 February 2000)

[36] Richard H. Love, “A comparison of volume scattering strength data with model calculations based on quasisynoptically collected fishery data”, J. Acoust. Soc. Am., **94**(4), 2255-2268, (1993)

[37] Charles w. Holland and Peter Neumann, “Sub-bottom scattering: a modeling approach”, J. Acoust. Soc. Am., **104**(3), 1363-1373, (1998)

[38] Dan Li, Dajun Tang and George v. Frisk, “Evaluation of sound propagation models used in bottom volume scattering studies”, J. Acoust. Soc. Am., **108**(5), Pt.1, 2039-2052, (2000)

[39] P.C. Hines, “Theoretical model of acoustic backscatter from a smooth seabed”, J. Acoust. Soc. Am., **88**, 324-334, (1990)

[40] A.N. Ivakin, “Sound scattering by random inhomogeneities of stratified ocean sediments”, Sov. Phys. Acoust., **32**, 492-496, (1986)

List of symbols/abbreviations/acronyms/initialisms

CW	Continuous Wave
DMOS	DRDC Atlantic Model Operating System
DND	Department of National Defence
DRDC	Defence Research & Development Canada
EMM	Environment Modeling Manager, an acoustic prediction component of PLEIADES
GSM	Generic Sonar Model
LFM	Linear Frequency Modulation
ONR	Office of Naval Research
PE	Parabolic Equation
PLEIADES	A research-level combat system designed and implemented by DRDC Atlantic
R&D	Research & Development
REA	Rapid Environmental Assessment
RMS	Root Mean Square
SE	Signal Excess
SRR	Signal-to-Reverberation Ratio
SWAMI	Shallow Water Active-sonar Modelling Initiative

This page intentionally left blank.

Distribution list

Document No.: DRDC Atlantic CR 2010-119

<u>LIST PART 1: Internal Distribution by Centre:</u>

3	DRDC Atlantic Library (1 hard copy, 2 CDs)
1	Dan Hutt, NL, TTCP MAR TP-9
1	Scientific Authority
1	Marcel Lefrançois
1	Jim Theriault
1	Garfield Mellema
1	John Osler
1	Paul Hines
1	Sean Pecknold
1	Dale Ellis
1	Mark Trevorrow
1	Brian Maranda
14	TOTAL LIST PART 1

<u>LIST PART 2: External Distribution by DRDKIM</u>

1	Library and Archives Canada, Attn: Military Archivist, Government Records Branch
1	(CD) NDHQ/DRDKIM
1	McCammon Acoustical Consulting, 475 Baseline Road, Waterville NS B0P 1V0
1	DMRS 5-3, HDHQ 101 Colonel By Drive Ottawa ON K1A 0K2
1	DSTM 7, DRDC, 305 Rideau St., Ottawa, ON K1A 0K2
1	Director, Underwater Battlespace CFMWC, MARLANT HQ PO Box 99000, Stn Forces Halifax, NS, B3K 5X5
2	SSO METOC MARLANT HQ PO Box 99000, Stn Forces Halifax, NS, B3K 5X5
8	TOTAL LIST PART 2

<u>22 TOTAL COPIES REQUIRED</u>

This page intentionally left blank.

DOCUMENT CONTROL DATA

(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

1. ORIGINATOR (The name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Centre sponsoring a contractor's report, or tasking agency, are entered in section 8.) McCammon Acoustical Consulting 475 Baseline Road Waterville NS B0P 1V0	2. SECURITY CLASSIFICATION (Overall security classification of the document including special warning terms if applicable.)

3. TITLE (The complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S, C, R or U) in parentheses after the title.)

A Literature Survey of Reverberation Modeling: with Emphasis on Bellhop Compatibility for Operational Applications

4. AUTHORS (last name, followed by initials – ranks, titles, etc. not to be used)

McCammon, D.F.

5. DATE OF PUBLICATION (Month and year of publication of document.) September 2010	6a. NO. OF PAGES (Total containing information, including Annexes, Appendices, etc.) 34	6b. NO. OF REFS (Total cited in document.) 40

7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

Contract Report

8. SPONSORING ACTIVITY (The name of the department project office or laboratory sponsoring the research and development – include address.)

Defence R&D Canada – Atlantic
9 Grove Street
P.O. Box 1012
Dartmouth, Nova Scotia B2Y 3Z7

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.) 11ca	9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.) W7707-098272
10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.)	10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.) DRDC Atlantic CR 2010-119

11. DOCUMENT AVAILABILITY (Any limitations on further dissemination of the document, other than those imposed by security classification.)

( ) Unlimited distribution
( ) Defence departments and defence contractors; further distribution only as approved
( ) Defence departments and Canadian defence contractors; further distribution only as approved
( ) Government departments and agencies; further distribution only as approved
( ) Defence departments; further distribution only as approved
(x) Other (please specify): Unlimited

12. DOCUMENT ANNOUNCEMENT (Any limitation to the bibliographic announcement of this document. This will normally correspond to the Document Availability (11). However, where further distribution (beyond the audience specified in (11) is possible, a wider announcement audience may be selected.))

Unlimited

13. ABSTRACT (A brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), (R), or (U). It is not necessary to include here abstracts in both official languages unless the text is bilingual.)

Recent publications of reverberation and scattering strength modeling are reviewed. Emphasis is placed on investigating operationally oriented models (as opposed to research oriented) that may be compatible with the Bellhop propagation model for use within the Environment Modeling Manager (EMM). Special attention is given to the research of Dr. Dale Ellis including his normal mode reverberation model, his clutter model approach, and his scattering strength model. Recommendations are made to consider adding the Ellis normal mode model and the Harrison closed form expressions to the Environment Modeling Manager to compliment Bellhop. It is recommended that a range of bottom scattering strength models be implemented to provide a choice of grazing angle dependences. It is recommended that the Gauss surface scattering strength model be investigated to possibly replace the Ogden-Erskine model. It is also recommended that the Ainslie angle/decay rate relationship be examined to possibly provide the experimental evidence for choosing one scattering strength kernel over another at each operational site.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (Technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus, e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

sonar; acoustic prediction; underwater warfare

This page intentionally left blank.

Defence R&D Canada

Canada's leader in defence
and National Security
Science and Technology

R & D pour la défense Canada

Chef de file au Canada en matière
de science et de technologie pour
la défense et la sécurité nationale

DEFENCE R&D DÉFENSE

www.drdc-rddc.gc.ca