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Acoustic Propagation and the Sea Surface

Literature Review

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Contract Report
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Canada

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Abstract

This report describes a review of current literature on the interaction of underwater sound with the sea surface. The document discusses current areas of scientific research on this topic, as well as the current capabilities of a few popular acoustic models. Recent scientific research shows that the creation of bubbles by wind-driven waves can have an important influence on transmission loss and reverberation. Under certain circumstances this is even true at moderate (low-kilohertz) frequencies. Most of the acoustic models currently in use for sonar performance prediction may not take all of the important interactions with the sea surface into account.

Résumé

Ce rapport contient une recension des écrits scientifiques sur l'interaction entre les sons sous-marins et la surface de la mer. Il présente les domaines de recherche actuels sur ce sujet, ainsi que les capacités présentes de quelques modèles populaires de propagation acoustique. Des recherches récentes ont démontré que la création de bulles par des vagues entraînées par le vent peut avoir une grande influence sur les pertes de transmission et la réverbération. Dans certaines circonstances, ces phénomènes sont importants, même aux fréquences moyennes (quelques kilohertz). Or, la plupart des modèles acoustiques actuellement utilisés pour prédire le rendement des sonars ne tiennent pas compte des interactions importantes entre les sons et la surface de la mer.

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Executive Summary

Introduction/Background

This work was undertaken as part of the Geoacoustic Parameter Sensitivity and Interaction Study. That project has included a number of numerical experiments to assess the sensitivity of a modeled acoustic field to various environmental perturbations. To date variations in the sea surface properties have not been considered in detail.

Results

The results presented are a summary of current scientific research into the interaction of underwater sound with the ocean surface. There are two primary methods by which the sea surface influences acoustic propagation: through reflection and scattering from the rough water-air boundary; and through scattering, absorption, and refraction by entrained air bubbles in the near-surface part of the water column. The relative importance of these mechanisms varies with frequency and wind speed. It is also noted that most commonly used acoustic models do not include wind-entrained bubbles as part of their environmental model, and so cannot be expected to produce high-fidelity predictions for environments where surface interactions are important.

Significance

The literature review presents the state of current knowledge, highlighting those areas that are of particular relevance for the environments and frequencies that have been the focus of the Geoacoustic Sensitivity Study and follow-on work to date. The report also points out a potential weakness in acoustic models that are in wide use at DRDC Atlantic and elsewhere.

Future Plans

It will be difficult to extend the current work on geoacoustic sensitivity to include a quantitative assessment of sensitivity to surface waves and wind unless the fidelity of surface models can be improved. We propose that this literature review could be used as a starting point for a more detailed investigation into potential improvements to Bellhop and/or PECan.

P.M. Giles; G.H. Brooke; D.F. McCammon; S.E. Dosso; M. Morley. August 2007. Acoustic Propagation and the Sea Surface: Literature Review. DRDC Atlantic CR 2007-105. Defence R&D Canada – Atlantic.

Sommaire

Introduction et contexte

Ce travail fait partie de l'Étude de sensibilité et d'interaction de paramètres géoacoustiques. Ce projet comportait un certain nombre d'expériences numériques permettant d'évaluer la sensibilité d'un modèle de champ acoustique à différentes perturbations du milieu. Toutefois, les variations des propriétés de la surface de la mer n'ont pas été considérées en détail.

Résultats

Nous présentons un résumé des résultats des recherches scientifiques en cours sur l'interaction des sons sous-marins avec la surface de l'océan. La surface de la mer influe sur la propagation acoustique de deux façons : par la réflexion et la diffusion par la frontière irrégulière entre l'eau et l'air; par la diffusion, l'absorption et la réfraction des bulles d'air entraînées près de la surface de la colonne d'eau. La contribution relative de ces deux mécanismes varie en fonction de la fréquence et de la vitesse du vent. On retiendra que dans les programmes de simulation acoustique les plus communément utilisés, le modèle du milieu ne tient pas compte des bulles créées par le vent, ainsi on ne peut s'attendre qu'ils produisent des prédictions très précises pour les milieux très affectés par les interactions avec la surface.

Importance

La recension des écrits scientifiques présente l'état des connaissances actuelles, souligne les domaines particulièrement importants pour les milieux et les fréquences qui ont fait l'objet de l'Étude de sensibilité géoacoustique et des travaux résultants réalisés jusqu'à maintenant. Notre rapport signale une faiblesse potentielle des modèles acoustiques largement utilisés à RDDC Atlantique et ailleurs.

Recherches futures

À moins d'améliorer la fidélité des modèles de surface, il sera difficile de poursuivre le travail actuel sur la sensibilité acoustique pour qu'il comprenne une évaluation quantitative de la sensibilité aux vagues à la surface et du vent. Nous suggérons que cette recension des écrits puisse servir de point de départ pour une recherche plus détaillée sur des améliorations possibles aux modèles Bellhop et PECan.

P.M. Giles, G.H. Brooke, D.F. McCammon, S.E. Dosso et M. Morley. August 2007. *Acoustic Propagation and the Sea Surface: Literature Review* (Propagation des ondes acoustiques et surface de la mer : une recension des écrits). RDDC Atlantique CR 2007-105. Defence R&D Canada – Atlantic.

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1 Introduction

1.1 Geoacoustic Parameter Sensitivity and Interaction Study

This document is one of the deliverables of the Geoacoustic Parameter Sensitivity and Interaction Study. Some background on that project, and a description of the deliverables, is provided in a companion document titled *Geoacoustic Parameter Sensitivity and Interaction Study: Summary of Work and Results*. The scope of this document, and its relationship to other deliverable reports, is described in the following section.

1.2 Document Objectives and Organization

The objective of this document is to provide a very brief review of the current state of knowledge about the influence of the sea surface on acoustic propagation in the ocean. The influence of the sea surface has not been addressed in any detail elsewhere in the Geoacoustic Parameter Sensitivity and Interaction Study or in previous work (see [1]).

Section 2 will provide a review of recent scientific literature that addresses the theory and measurement of acoustic interaction with the sea surface. This includes a discussion of the interaction with the rough sea surface and a discussion of the influence of bubbles in the water column near the surface.

Section 3 briefly discusses the way that current acoustic propagation models treat the sea surface. It focuses particularly on those models that have been used elsewhere in the Geoacoustic Parameter Sensitivity and Interaction Study.

Section 4 discusses the conclusions of the review and makes suggestions for future work.

2 Literature Review

This section contains a review of current scientific literature. It is divided into three subsections. Section 2.1 discusses reflection and scattering from the sea-air interface. Section 2.2 discusses interaction with air bubbles in the near-surface water column. Finally, section 2.3 discusses the interaction between these two effects. This organization is also, in some sense, chronological. The earliest theoretical treatments of the surface interaction tended to neglect the influence of bubbles on acoustic propagation, whereas recent work has shown that the presence of bubbles can have both a direct and an indirect influence on transmission loss.

2.1 Reflection and Scattering From the Interface

When a plane sound wave in water hits a smooth sea surface, nearly all of the incident energy is coherently reflected in the forward direction. As the surface becomes rougher, sound is also scattered in the backward and out-of-plane directions by the surface irregularities.

This aspect of the surface-interaction problem has not seen a great deal of recent investigation. A review of sea surface scattering by E.Y.T. Kuo in 1988 [2] provided an analysis of a number of approaches based on perturbation methods. The surface reflection models provided in most modern acoustic modelling packages are similar to those in use twenty years ago, or even longer (e.g. [3]-[5]).

It should be noted that the perturbation models characterize the sea surface roughness statistically and do not attempt to model what might be called “range-dependent” surface properties – individual waves or wave trains. For most sonar applications, this gives a sufficient level of fidelity.

In order to estimate surface loss due to the surface roughness, it is necessary to characterize the wave spectrum. Typically this spectrum is estimated from a measured or forecasted wind speed. Two popular models for estimating the wave spectrum are the Neumann-Pierson model [6] and the Pierson-Moscowitz model [7].

2.2 Attenuation, Scattering and Refraction Due to Bubbles

The presence of bubbles in the water column influences acoustic propagation in a number of ways. In addition to increasing the acoustic attenuation, the presence of bubbles increases the compressibility of the water mass, thereby decreasing sound speed. The combined effect can be expressed as a complex sound speed (or equivalently a complex index of refraction). A comprehensive derivation of expressions for the attenuation and sound speed in a bubbly liquid was published by Commander and Prosperetti in 1985 [8].

The effect of wave-generated bubbles on propagation has been an area of considerable recent research (e.g. [10]-[13]). This has been partly driven by observations that models of scattering from the rough interface cannot properly account for the observed surface loss or backscatter in many experiments.

Propagation losses due to bubbles are strongly frequency-dependent and much of the recent research has been focussed on frequencies above 10 kHz. Dahl's paper in *High Frequency Ocean Acoustics* [13] considers total energy loss for frequencies in the 20 kHz range, using data from the ASIAEX experiment to ratify models of bubble-driven energy loss. The results suggest that there are three important wind-speed domains for loss at high frequency. At low wind speeds (< 5-7 m/s) there is no discernable attenuation of total energy. In moderate winds of 7-12 m/s, attenuation increases with wind speed. Finally, at high wind speeds from 12-15 m/s, there is near total occlusion of the sea surface, and bubble-mediated energy loss becomes bounded by scattering from bubbles.

Backscatter by the bubble layer has also been a topic of interest, again partly driven by the fact that theories of surface scattering could not account for observations from reverberation experiments (e.g. [14]). A 1993 paper by Gilbert [15] provided a comprehensive discussion of the contribution of bubbles to backscatter, treating the entrained bubbles as a stochastic layer and showing that the bubble layer makes an important contribution to surface backscatter.

Recent research has also extended to include "range-dependent" bubble population models, examining the influence of the spatial structure of the bubble field. In a 2001 paper, Norton and Novarini [12] examine the data from a long-term experiment and conclude that at 2 and 4 kHz, the main mechanism responsible for the excess loss observed in windy conditions is the "patchy" nature of the sub-surface bubble field. In other words, the range-dependence of the bubble population is an important factor in quantifying surface loss.

To include the effect of entrained bubbles in an acoustic propagation prediction, it is necessary to generate a model of the bubble population – the number of bubbles in a given volume of sea water with a given radius. M.V. Hall proposed an empirical model of bubble population as a function of wind speed in 1989 [16] that is still in fairly wide use today. Some studies have reported (e.g. [17]) a modification to this model by Novarini and Norton which accounts for the "latest findings on smaller bubbles." The modification, sometimes referred to as the Hall-Novarini model, may be described in [18]; we did not succeed in obtaining a copy of that document for this review.

2.3 Combined Effects

A paper published by M.A. Ainslie [19] in December 2005 gives a comprehensive analysis of the effect of wind-generated bubbles on propagation loss in shallow water in the 1-4 kHz frequency range. Because this is a recent paper, and because the Geoacoustic Parameter Sensitivity and Interaction Study has been especially concerned with frequencies in this range and in this type of environment, we will give a more complete summary of reference [19]. The paper considers the effect of wind-generated bubbles on both the sound speed and the "extinction coefficient," which combines the effect of attenuation and scattering into a single loss parameter.

Ainslie points out that although the theory of surface scattering from a rough boundary is well understood, there is often a significant quantitative mismatch between theoretical predictions and observations, with observed losses exceeding predicted losses by as much as a factor of three. As noted above, it is generally recognized that air bubbles are the most likely source of these discrepancies. Ainslie argues, however, that for low to moderate frequencies bubbles are unlikely to be the *direct* cause of increased attenuation. This argument is partly based on previous work by Norton and Novarini [18], who reached the conclusion that attenuation and scattering by bubbles should be small in the low-kilohertz region. Ainslie also notes that the observed surface loss is seen to be proportional to $f^{3/2}v^4$, where f is the acoustic frequency and v is the wind speed. The functional form of this dependence matches theoretical predictions for loss due to scattering from the rough surface, although the theoretical proportionality constant is too small to match the observations.

Ainslie uses measurements made by Weston and Ching [20] for comparison to a number of analytical results. To model surface roughness, Ainslie considers both the Neumann-Pierson spectral model and the Pierson-Moskowitz spectral model referred to above. To model bubble density with depth, he uses the near-surface Hall-Novarini model, also referred to above.

Ainslie finds that attenuation and scattering effects are small for frequencies less than about 3 kHz, accounting for losses as high as about 0.1 dB/m for a frequency of 3 kHz and a wind speed of 12 m/s, but generally being well below that value. Above 3 kHz, resonance effects can become important and extinction due to bubbles grows rapidly. On the other hand, the sound speed deficit near the ocean surface can be significant, even for low frequencies, reaching as much as 25 m/s at the sea surface (mostly independent of frequency) for a 12 m/s wind speed. The sound speed deficit decreases with depth, being equal to about 10 m/s at 1 m, and disappearing altogether at 10 m depth.

The central conclusion of the paper [19] is that bubbles are responsible for the discrepancy between modeled and observed surface reflection losses, but through an *indirect* mechanism. Specifically, the bubble layer created by wind-driven waves modifies the sound speed profile, increasing interaction with the surface, and therefore increasing the magnitude of the reflection loss. When the sound speed modification is taken into account, rough surface reflection can successfully account for the observed surface loss. Attenuation and scattering due to bubbles is a negligible source of energy loss in the low-kilohertz frequency range.

3 Acoustic Propagation Models

In a 1985 paper in the OCEANS'85 Conference Proceedings [21], A.I. Eller assessed the status of surface loss models in sonar performance models:

> "One problem area in particular that has not been adequately developed, and which in some cases is the weak link in sonar performance modeling, is the scattering of acoustic energy at the rough sea surface. Currently used models for surface reflection loss, as implemented in sonar performance models, often give vastly conflicting surface loss predictions, which in turn lead to correspondingly severe discrepancies in predicted propagation loss. … side effects of large modeling discrepancies are that the entire modeling effort loses credibility and, more important, users of model predictions are left with unresolved, contradictory guidance."

(Eller and his co-authors presented a similarly dismal view of surface reverberation models in an earlier OCEANS paper [22].)

Eller's concerns about the discrepant predictions of different models are not still applicable to the same degree today. However, as noted above most widely-used sonar prediction models still use surface reflection models that were refined during that period.

A few specialized models have been developed specifically for use in high-fidelity studies of surface interactions. Norton et al., in 1995, described one such model [23]. The approach combines a PE-based acoustic propagation model with a conformal mapping technique to model deterministic realizations of the rough sea surface.

3.1 Models Used in This Project

In the Geoacoustic Parameter Sensitivity and Interaction Study, we have made extensive use of three different acoustic propagation models. The three models – the ray-based model Bellhop, the parabolic equation model PECan, and the ray-based components of CASS/GRAB – are of special interest to DRDC-Atlantic, and are also in wide use elsewhere. Although the models have not been used to model surface interaction in this study, it is useful to consider their capabilities in this regard.

In the ray-based model Bellhop, a rough sea-air interface can be approximated by specifying a reflection coefficient as a function of grazing angle. The reflection coefficient table must be calculated externally and provided to Bellhop as an input (this has been done for surface studies, for example, in [24]). Bubbles in the water column are not modeled, although the effects could be included in the specified volume attenuation and the sound speed profile.

The parabolic equation model PECan models the upper boundary as a rough free surface with Gaussian statistics, with the wave spectral characterization being provided as an input. At the frequencies where PECan has historically been used, interaction with the sea surface is probably not a dominant influence on the transmission loss, and interaction with air bubbles is probably even smaller. However, using modern computers PECan can be comfortably used for passive modeling in the mid-kilohertz range, and we have done so during the Geoacoustic Parameter Sensitivity and Interaction Study. As previously discussed, Ainslie [19] has shown that bubbles can have a significant impact at these frequencies.

In addition to accepting a table of coefficients, CASS/GRAB can call on five different surface reflection models, each of which takes either a wind speed or a wave height as an input parameter. CASS/GRAB also includes models for bubble attenuation. The CASS/GRAB Users Guide comments that bubble attenuation can either be incorporated into the volume attenuation coefficient, or added to the surface reflection coefficient. It is also noted, however, that the latter approach appears to be problematic.

4 Conclusions and Future Work

4.1 Conclusions

Based on this review of the current literature, it appears that most widely-used acoustic propagation models are lagging behind the current state of scientific knowledge. For high-frequency propagation, sound can be significantly attenuated by bubbles arising from wind-driven waves, and the rough sea-air interface may be entirely occluded by the bubble layer at high wind speeds. Even at mid-kilohertz frequencies, it appears that the influence of entrained air bubbles can be significant in some environments, through their modification of the sound speed profile in the upper few metres.

Most acoustic propagation models do not include the influence of bubbles in even a range-independent way, instead merely translating the wind speed or wave height into an interfacial roughness.

4.2 Future Work

To date the Geoacoustic Parameter Sensitivity and Interaction Study has not addressed in detail the sensitivity of acoustic propagation to the properties of the sea surface. Future extensions to this work might attempt to perform experiments on that sensitivity, similar to the experiments that have already been performed on sensitivity to water column and ocean bottom properties. However, the realism of those experiments might be limited by the current state of available acoustic propagation models. It may be possible, in some models, to mimic the effect of the bubble layer by including depth-dependent volume attenuation and sound speed profile variations.

GD Canada suggests that DRDC Atlantic should consider future development of their in-house acoustic models, especially the ray-based model Bellhop-DRDC which is commonly used to model propagation at high frequencies where surface interaction is important. This future work could take the form of additions to Bellhop itself, or the creation of a pre-processing module that appropriately modifies the inputs to Bellhop. A detailed study of this problem is beyond the scope of this project, but this report can serve as a starting point for future research.

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List of symbols/Abbreviations/Acronyms/Initialisms

DND	Department of National Defence
OPI	Office of Primary Interest
R&D	Research & Development

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