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DEFENCE R&D DÉFENSE

GEOACOUSTIC SENSITIVITY STUDY

Phase 1: Literature Review

Peter Giles
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Contract Number: W7707-042837

Contract Scientific Authority: Sean P. Pecknold, (902) 426-3100 ext 222

Defence R&D Canada – Atlantic

Contract Report
DRDC Atlantic CR 2006-048
May 2006

Canada

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Abstract

This report covers the work carried out by General Dynamics Canada during phase I of the Geoacoustic Sensitivity Study. The report consists of a literature review covering the topics of geoacoustic and oceanographic uncertainty and variability, and the sensitivity of measured acoustic quantities to these variations. This document is an interim report as specified in the project statement of work.

Résumé

Le présent rapport traite des travaux effectués par General Dynamics Canada durant la phase I de l'étude sur la sensibilité géoacoustique. Il consiste en une revue de la littérature sur l'incertitude et la variabilité géoacoustiques et océanographiques, ainsi que sur la sensibilité des grandeurs acoustiques mesurées à ces variations. Le présent document constitue un rapport provisoire, tel que précisé dans l'énoncé de travail du projet.

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Executive Summary

Introduction

This report covers the work carried out by General Dynamics Canada during phase I of the Geoacoustic Sensitivity Study. The report consists of a literature review covering the topics of geoacoustic and oceanographic uncertainty and variability, and the sensitivity of measured acoustic quantities to these variations. The report also includes an overview of recommended acoustic models for continuation of the study and describes the development of a sensitivity measure to evaluate geoacoustic sensitivity. This document is an interim report as specified in the project statement of work.

Results

The literature includes a fairly large number of ocean experiments where a detailed characterization of the shallow-water environment has been paired with repeated acoustic measurements. The environmental characterizations are very useful for determining typical values and variabilities for environmental parameters of interest. There are also several papers that derive analytical or quasi-analytical expressions for the sensitivity of the acoustic field to environmental perturbations. The bulk of the work summarized in this report concerns characterizing and/or reducing uncertainty in acoustic predictions. Based on the literature reviewed, the water column sound speed profile appears to have the most significant effect on acoustic propagation; the temporal and spatial variability associated with internal waves seems to be especially relevant in shallow water. On the other hand, it appears that this subject has had more scrutiny than the influence of the bottom properties. It is concluded that, of the bottom-related properties, the bathymetry, compressional sound speed (and possibly its gradient), and sediment layer depth should be included in the sensitivity analysis.

Concerning the choice of models, it is determined that a comparison using more than one model would be advantageous, since there can be significant differences between models even for the same nominal environment.

Significance

Much work remains to be done at the system level before sonar performance prediction models can achieve practical improvements in shallow water areas. An improvement in knowledge of the sensitivity of sonar model performance to geoacoustic and oceanographic variability and uncertainty will improve the ability of DRDC Atlantic to provide relevant and accurate sonar predictions and will determine what improvements in Rapid Environmental Assessment tools and models will prove most effective.

Future Work

The Geoacoustic Sensitivity Study includes two further phases. These are an estimate of the parameters of importance, and numerical modeling and data comparison to validate the previous work done. This study is ongoing, and further work, both experimental and theoretical, may follow as part of the Rapid Environmental Assessment project.

General Dynamics Canada Ltd. 2006. Geoacoustic Sensitivity Study Phase I: Literature Review. DRDC Atlantic CR 2006-048. Defence R&D Canada – Atlantic.

Sommaire

Introduction

Le présent rapport traite des travaux effectués par General Dynamics Canada durant la phase I de l'étude sur la sensibilité géoacoustique. Il consiste en une revue de la littérature sur l'incertitude et la variabilité géoacoustiques et océanographiques, ainsi que sur la sensibilité des grandeurs acoustiques mesurées à ces variations. Il comprend également un aperçu de modèles acoustiques recommandés pour la poursuite de l'étude et il décrit l'élaboration d'une mesure de la sensibilité pour évaluer la sensibilité géoacoustique. Le présent document constitue un rapport provisoire, tel que précisé dans l'énoncé de travail du projet.

Résultats

La littérature comprend un assez grand nombre d'expériences en milieu océanique où une caractérisation détaillée du milieu en eau peu profonde a été associée à des mesures acoustiques répétées. Les caractérisations environnementales sont très utiles pour déterminer les valeurs et variations types des paramètres environnementaux d'intérêt. La littérature comprend également plusieurs documents sur le calcul d'expressions analytiques ou quasi analytiques de la sensibilité du champ acoustique aux perturbations de l'environnement. L'essentiel des travaux résumés dans le présent rapport porte sur la caractérisation ou la réduction de l'incertitude dans les prévisions acoustiques. D'après la revue de la littérature, l'effet le plus important du profil de la vitesse du son dans la colonne d'eau semble être sur la propagation acoustique; la variabilité spatiale et temporelle liée aux ondes internes semble particulièrement pertinente en eau peu profonde. Par contre, il semble que ce sujet ait fait l'objet d'une plus grande attention que l'incidence des propriétés du fond. En conclusion, la bathymétrie, la vitesse de propagation de l'onde acoustique de compression (et possiblement son gradient) et la profondeur de la couche de sédiments sont les propriétés liées au fond qui devraient être incluses dans l'analyse de la sensibilité.

En ce qui concerne le choix de modèles, il a été déterminé qu'une comparaison à l'aide de plus d'un modèle serait avantageuse puisqu'il peut y avoir des différences importantes entre les modèles et ce, même pour le même environnement nominal.

Portée

Il reste beaucoup de travail à faire à l'échelle du système avant que les modèles de prévision des performances du sonar permettent des améliorations concrètes en eau peu profonde. Une amélioration des connaissances sur la sensibilité du rendement du modèle de sonar à la variabilité et à l'incertitude océanographiques et géoacoustiques permettra d'améliorer la capacité de RDDC Atlantique à formuler des prévisions exactes et pertinentes en ce qui concerne le sonar et déterminera les modifications à

apporter aux outils et modèles d'évaluation environnementale rapide qui seront les plus efficaces.

Recherches futures

L'étude sur la sensibilité géoacoustique comprend deux autres phases : une estimation des paramètres importants ainsi que la modélisation numérique et la comparaison de données afin de valider les travaux antérieurs. Cette étude se poursuit, et d'autres travaux, expérimentaux ou théoriques, pourraient être réalisés dans le cadre du projet d'évaluation environnementale rapide.

General Dynamics Canada Ltd. 2006. Geoacoustic Sensitivity Study Phase I: Literature Review. DRDC Atlantic CR 2006-048. Defence R&D Canada – Atlantic.

Table of Contents

1. Introduction

1.1 Identification

General Dynamics Canada (GD Canada) performed this work to complete phase I of the Geoacoustic Sensitivity Study (Sol. No. W7707-042837/A) for DRDC Atlantic.

<u>**Scientific Authority**</u>
Dr. Sean Pecknold,
DRDC Atlantic,
Tel 426-3100 ext. 222

1.2 Background

The objective of the Geoacoustic Sensitivity Study is to determine the sensitivity of measured acoustic quantities on variability in geophysical and oceanographic conditions.

Phase I of the project, as specified in the RFP Statement of Work, consists of a literature review covering the topics of uncertainty, variability, and sensitivity.

1.3 Objectives and Scope

The objective of the Geoacoustic Sensitivity Study is to determine the sensitivity of measured acoustic quantities on variability in geophysical and oceanographic conditions.

Phase I of the project, as specified in the RFP Statement of Work, is a literature review covering four topics:

Uncertainty of measured oceanographic and geophysical parameters;

The effect of changes in measured or input oceanographic and geophysical parameters on acoustic propagation, including transmission loss, reverberation levels, and signal excess. This includes literature considering these effects both from the perspective of the physics involved and in the use of numeric and analytic models;

The effect of random variability of geophysical and oceanographic parameters on acoustic measurables; and

The correspondence of acoustic model input parameters to physical parameters, and the degree to which acoustic models need inputs specified (e.g. at what rate/spacing do parameters such as sound speed need to be measured, or at what point is a set of bottom layers under specifying or over specifying a problem).

1.4 Reasons for Report

The purpose of this report is to:

a. Describe the work undertaken during phase I;

b. Present the results of the literature search with the aim of meeting the objectives of phase I;

c. Give recommendations for work to be conducted in phase II; and

d. Provide the scientific authority with a basis for either extending phase I or initiating work on phase II.

1.5 Methods Employed

This work was carried out by two local GD Canada employees with support from Ottawa, and two external consultants (Dr. Diana McCammon and Mr. Bob Trider). Dr. Stan Dosso offered some guidance. Regular meetings have been held with the scientific authority.

1.6 Organization of Document

This document is an informal interim report, and is not strictly organized according to the contractor’s report template.

Section 2 provides some historical background about geoacoustic models of the ocean, which was provided by Dr. Diana McCammon. Section 3 begins the review of current literature with summaries and annotated bibilographies for work done under the ONR Uncertainty DRI. Section 4 continues the review with an annotated bibiography for work not directly connected with the ONR initiative. Section 5 discusses four acoustic propagation models that were suggested by the scientific authority for use in this study. Section 6 presents a summary of the literature review and some recommendations for phase II.

2. Historical Background

A geoacoustic model of the ocean and the ocean bottom is one that represents the environment in terms of the quantities that are particularly important in the prediction of acoustic energy interactions. Some of these parameters are difficult to measure and must be inferred from other experiments using acoustic techniques. Thus, some parameters may not be "real" representations of the geophysical nature of the sediment, but will reflect the method of extraction.

A notorious example of an inaccurate representation of geophysical values by geoacoustic ones occurred in the 1980's when the Bottom Loss Upgrade (BLUG) database was being assembled. The scientists found that in order to reproduce a loss of up to 30 dB at 100 Hz while also obtaining an anomalously low loss of 4 dB at 1600 Hz in the Hatteras Abyssal Plain, they had to introduce an artificial thin layer and imbue it with the physical properties of stainless steel. Clearly that model is a geoacoustic one.

This section gives some background on the historical development of geoacoustic models of the sea floor, using the BLUG database as a case study.

2.1 Definitions of Parameters

2.1.1 Basic Geoacoustic Profiles

The basic set of geoacoustic parameters consist of the compressional sound speed, the density, the attenuation and the layer thickness of each defined layer of the seabed. In 1982, Chapman and Ellis presented a method for deriving the basic set of parameters at two shallow water sites using a combination of measurements and model adjustments to match theory and experiment. They analyzed sub-bottom vertical profiles to determine sediment type and thickness, seismic refraction data to estimate sound speeds, and dispersion analysis to estimate volume attenuation[1]. There are several papers of interest in a book published in 1980 entitled *Bottom Interacting Ocean Acoustics* that discuss the determination of geoacoustic models for shallow water regions[2].

The basic difficulty in defining a geoacoustic model of the bottom, apart from the complex task of extracting parameters from diverse sources, is that the seabed's composition is variable and it resists being divided neatly into constant property layers. Hence, some simplification and averaging is always necessary.

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[1] Chapman, D.M.F., and D.D. Ellis, "Geo-acoustic Models for Propagation Modelling in Shallow Water," Presented at 103rd Meeting of the Acoustical Society of America, Chicago, Illinois, 27 April, 1982.
[2] Bottom Interacting Ocean Acoustics, W.A. Kuperman and F.B. Jensen, Eds., Springer-Verlag, New York, 1980.

Paul Vidmar, a well known scientist in the area of bottom characterizations, suggested defining four sets of geoacoustic profiles, increasing in complexity[3]. The first profile contains only the fluid parameters of the water-sediment interface, from which a surficial reflection coefficient can be developed. The second includes a model of the sediment volume by adding a depth dependent compressional wave velocity and absorption to model refraction and attenuation within the sediment. The third adds substrate or basement parameters and a shear wave velocity at the basement to model losses due to conversion to shear. The fourth and most detailed profile adds the depth dependent shear wave velocity and shear wave absorption in the sediment and models the re-conversion of energy back to compressional waves. Vidmar argued that the use of a particular one of these four geoacoustic profiles will depend on frequency and grazing angle. He suggested that thick sediments at high frequency can be modeled using the first profile, as specular reflectivity is the dominant process. For thick sediments at low frequencies or grazing angles low enough to afford strong refraction in the sediment, the second profile will suffice. In thin sediments at high frequencies, the basement will play an acoustic role as a reflector, and in thin sediments at low frequencies, conversion between compressional and shear will take place at the basement and within the sediment volume. Vidmar is, in effect, arguing for choosing the least complex model that will adequately cover the dominant mechanisms for any given circumstance. This certainly makes sense if an inversion for geoacoustic parameters is being executed, because those parameters that are not important will almost certainly get erroneous values from the inversion process.

2.1.2 BLUG Profiles

In 1975, the U.S. Navy began sponsoring research to create a global database of acoustic properties of the seafloor which was called the Bottom Loss Upgrade (BLUG). The BLUG concept was to combine available geophysical data on the global distribution of sediment types with estimates of sound speed, attenuation and apparent impedance deduced from bottom loss data. The relevance of a review of the history of BLUG to the topic of uncertainty (Task phase I, a and b) lies in the documented difficulties encountered in trying to derive the BLUG parameters and the extent to which they were reliable. In some sense, the degree of empiricism and averaging that occurred in the creation of BLUG is directly attributable to the variability of the bottom geophysical properties and would be faced by anyone inverting for geoacoustic profiles.

The early BLUG used nine parameters to describe the characteristics of the sea floor in addition to the sediment thickness. Table 1 lists these parameters and the resolution of the database, which gives some indication of the expected variability or precision

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[3] Vidmar, P.J., “Linked Sets of Acoustical Processes and Geoacoustic Profiles Describing the Interaction of Sound with a Class of Sea-Floor Structures,” *Acoustics and the Sea-Bed*, N. G. Pace, Ed. Bath University Press, Bath, UK, 1983.

of measurement expected[4]. This initial BLUG parameter set was not a true geoacoustic profile, but a hybrid parameter set developed for predicting low frequency (50-1000 Hz) bottom loss in deep water environments. The geophysical part consists of the terms relating to the fluid sediment layer. The empirical part contains the reflectivity of the basement and the thin layer descriptors used to give frequency dependence to the surface impedance. The shallow water areas in the North Atlantic (all regions shallower than 800m) were given a single geoacoustic province consistent with a sediment type of sandy silt and silty sand as listed in the fourth column of the table. The inadequacy of this single default parameter set for all shallow water areas is obvious.

2.1.3 Shallow Water BLUG

In 1994, Vidmar and Monet released a shallow water extension to the BLUG database[5] to extend the database shoreward to depths as shallow as 50m. The major challenges were to define the appropriate parameter values for BLUG in shallow water and to determine methods for extrapolating parameter values based on limited acoustic data. The major change to the parameter set was the introduction of an exponent of the frequency dependence of the attenuation. The deep water algorithm assumes the exponent is 1.00 (linear dependence on frequency) while values between 1.00 and 2.00 were needed for the shallow water areas. A significant change to the parameter inversion technique was the introduction of an adiabatic normal mode model for inversions using transmission loss data, supplanting the old ray based analysis of bottom loss data.

TABLE 1. ORIGINAL BLUG PARAMETERS, RESOLUTION OF DATA BASE AND EXAMPLE VALUES.

PARAMETER	RESOLUTION	EXAMPLE DEEP WATER VALUES	SHALLOW WATER DEFAULT VALUE
Velocity ratio, R	0.005	0.995, 1.105, 1.200	1.090
Velocity Gradient, g (s^{-1})	0.1	2.1, 0.9, 3.5	20.0
Sediment density, ρ (g/cc)	0.01	2.64, 2.70, 1.87	1.80

4 Jim Kohsmann, Naval Oceanographic Office, Acoustics Division, "Draft of LFBL Upgrade Standards Strawman," conveyed to Diana McCammon by personal communication, 1991.

5 Vidmar, Paul J. and William F. Monet, "Development of the Shallow water Extension of the Bottom Loss Upgrade," Science Applications International Corporation, AEAS Report 95-001, Office of Naval Research, Advanced Environmental Acoustic Support (AEAS) Program, Sept. 1994.

Surficial attenuation, k_0 (dB/m @ 1kHz)	0.0005	0.0005, 0.0105	0.30
Attenuation gradient, γ (dB/m/m @ 1kHz)	0.00005	0.00005, 0.00125	-0.0006
Thin Layer density, ρ_t (g/cc)	0.05	4.15, 5.25, 4.3	--
Beta Value, β	0.1	-0.5, 1.1, 15.2	-0.97
Thin layer thickness, t_t (m)	0.01	0.22, 0.04, 1.56	--
Basement reflectivity, R_{sub}	0.05	0.25, 0.50, 0.75	0.10
Sediment thickness, t (0.1 seconds)	0.05	1.15, 0.35, 2.50	

2.1.4 Shallow Water BLUG Database Deficiencies

Some interesting problems arose in the development of this database. The following is a synopsis of those difficulties reported in reference 5.

First, there was a question about the interpretation of the range variability of measured propagation loss. Some data showed localized decreases in propagation loss at some frequencies that was deemed too large to be caused by range variability of seafloor parameters. It was postulated that a passing ship may have added energy in some frequency bands causing temporary changes in the transmission loss.

Secondly, the propagation data used in the analysis was octave averaged. This averaging removed some problems associated with the oscillatory nature of the power spectra of explosive sources but also obscured the modal interference pattern that could have been used to identify range variability of the seafloor parameters.

Thirdly, the propagation data was not collected at short enough ranges to determine the depth dependence of the geoacoustic parameters because the longer range propagation was dominated by the lowest order mode which has little penetration into the seafloor.

Fourthly, the data collection sites along the east coast of the U.S. did not sample many of the sediment types found in shallow water. Parameters for low porosity materials such as gravel were based purely on extrapolation of values from higher porosity sediments. The properties of rock outcrops and thinly sedimented areas were not sufficiently sampled; however the correlation of possible rock outcrop areas and significant changes in propagation loss with range suggested that outcrops have an important effect on shallow water propagation.

Lastly, the sediment thickness, as listed in the Lamont Doherty Geological Observatory database, was defaulted to 0.2 seconds two-way travel time (about 75 m) in all areas shallower than 800m. In areas along the continental slope and rise, this database listed enormous thicknesses of sediment because the database made no distinction between consolidated and unconsolidated materials, even though they have vastly different acoustical properties. The modeling of acoustic data indicates that the depth to the first reflector, and not the depth to the basalt, is the proper definition of acoustically relevant sediment thickness in shallow water. This has caused a great deal of confusion to the users of the data base.

This review of the BLUG geoacoustic database creation is meant to highlight some of the difficulties and uncertainties that accompany any geoacoustic profile. The inherent variability of the physical properties of the seafloor are exacerbated by the uncertainty introduced in the inversion, whether it be errors in measurement, poor data, uncertainty in the interpretation of the data, or missing data.

2.1.5 BLUG Sensitivity Studies

Sensitivity studies[6] carried out during the development of the shallow water BLUG pointed out that only the first four parameters of the database shown in Table 1, plus the attenuation frequency exponent, have an important role in determining TL from 50-1000 Hz at longer ranges in shallow water. Part of this conclusion is due to the high attenuation and velocity gradient of shallow water sediments and part to the fact that the sediment thickness had a database value of about 75m. The high attenuation eliminates the higher order modes that penetrate deeply into the sediment. Only the lowest order modes, that have the lowest attenuation, carry energy to long range. The high velocity gradient keeps the lowest order modes from penetrating very far into the sediment. Hence propagation to long range tends to be dominated by the properties of the upper 50 m of sediment over which the attenuation changes little. The lowest order modes do not penetrate to the substrate and do not interact with the basement to generate shear waves.

2.2 Geophysical Database (GDB)

The Geophysical Database (GDB) is a database of geophysical properties of the seafloor being developed by the Naval Oceanographic Office (NAVOCEANO) to support prediction of transmission loss in shallow water. My reference to this database is a critique written by Paul Vidmar[7]. In his critique he describes GDB as containing thickness, density, compressional velocity, compressional attenuation, shear velocity and shear attenuation for each layer above geologic basement. He was tasked to evaluate its performance in Martha's Vineyard, and he employed a normal mode program KRACKENC, a full physics model that includes shear.

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[6] Vidmar, Paul J. and W.F. Monet, "Development of the Shallow Water Upgrade of LFBL," Science Applications International Corp, TR# 94/1013, 1994.

[7] Vidmar, Paul J., "An evaluation of the NAVOCEANO Geophysical Database for the area south of Martha's Vineyard," SAIC-95/1373, Naval Oceanographic Office, Stennis Space Center, MS, December 1995

Vidmar's conclusions were that the GDB did not provide a gradient for the compressional velocity or attenuation, and therefore would not properly allow energy to refract with a layer. It also assumed a linear dependence on frequency for its attenuations whereas his research has shown that the frequency dependence could be as high as quadratic in shallow water areas. Finally, Vidmar found the shear velocity values in GDB were too large.

His suggestions for GDB improvement can be taken as general guidelines for any geoacoustic profile:

- Include parameters affecting acoustics. Parameters such as the velocity gradient are needed to model major acoustic processes. Others such as the shear velocity of the substrate are not needed because they have little impact on the acoustic field.
- Increase the level of detail. Increase the number of layers in the profile to the maximum extent supported by the travel time and other data. Collapsing smaller layers into a larger layer implements an assumption that the smaller layers do not have a major effect on the acoustics at frequencies of interest. In essence, it imposes an unknown maximum frequency for reliable acoustic predictions. Leaving the smaller layers in the profile allows the acoustic model to make that determination on the basis of the bottom interaction mechanisms.

2.3 High Frequency Geoacoustic Profiles

At the upper end of the frequency range assumed in this task, 10 kHz, the APL-UW High-Frequency Ocean Environmental Acoustic Models Handbook[8] provides a geoacoustic profile and equations for loss predictions. In their comments, they state that the modeling of the ocean bottom is confined to the top tens of centimetres because of the high attenuation of sound in the sediments at high frequencies. The upper few centimetres of sediment are more water-like than the sediment in deeper layers, especially for soft sediments like silts and clays. Unfortunately, quantitative geoacoustic data on this centimetres-thick transitional layer are almost nonexistent. With notable exceptions, the layer is either ignored outright or destroyed during processing of the collected sediment.

The geoacoustic profile is modeled using just three parameters: density, sound speed and loss. The report states that while the data available strongly suggest the existence of significant gradients in porosity (hence density), along with generally weaker gradients in sound speed and attenuation, their modeling efforts were constrained by the fact that there were not enough simultaneous acoustic and geoacoustic data with the necessary level of detail to construct a realistic model. Thus the sediments are

[8] "APL-UW High Frequency Ocean Environmental Acoustics Models Handbook," APL-UW TR 9407 / AEAS 9501, Applied Physics Laboratory, University of Washington, October 1994.

modelled as a simple, semi-infinite fluid half-space which is assumed to be statistically homogeneous both in the horizontal and in the vertical. This avoids complicated models which would have included more detailed physics, at the cost of ill-defined bounds and poorly supported relationships for the appropriate parameters.

The handbook states that the error in forward loss is approximately the same size in dB as the loss itself. That is, for a soft, clayey bottom, the predicted loss at 5 degrees was about 8 dB, and the data near this angle were within 6 dB of the prediction.

3. ONR Uncertainty DRI

As noted in the proposal submitted by GD Canada, the literature search described here relies heavily on the work of the *Capturing Uncertainty* Directed Research Initiative (DRI) of the US Office of Naval Research (ONR). This research initiative will hereafter be referred to as the Uncertainty DRI[9].

The Uncertainty DRI was initiated in fiscal year 2000/01 and ran through fiscal year 2004/05. The multidisciplinary effort involved ocean modeling, physical oceanography, ocean acoustics, signal processing, and sensing/ information dominance. At the ouset, the ultimate goal of the DRI was expressed as follows: *to develop a formalism for capturing, calculating, and representing uncertainty*.

Given the overlapping areas of interest, and since the Uncertainty DRI recently concluded its work, we believe that this will serve as an appropriate starting point for the Geoacoustic Sensitivity Study.

Through her personal contacts, Dr. Diana McCammon has been able to obtain the final (2005) reports from three of the contributing teams, including lists of publications. Each of the following sections will contain relevant information and quoted exerpts from those final reports, which have not yet been made available to the public. They can be made available to the scientific authority upon request. Note that there is significant overlap between the different teams.

3.1 UNITES Team

The UNITES (Uncertainty and Interdisciplinary Transfers Through the End-to-End System) team of the Uncertainty DRI was led by Philip A. Abbot of OASIS Incorporated. This interdisciplinary team included experts on the environment (physical oceanography and bottom geology), ocean acoustics (propagation, ambient noise, reverberation and signal processing), and tactical sonar systems.

The UNITES Team objectives were: to develop generic methods to characterize, parameterize, and prioritize sonar system variabilities and uncertainties; to construct, calibrate and evaluate uncertainty and variability models for sonar systems and their components; and to transfer uncertainties from the acoustic environment to the sonar system in order to effectively understand sonar performance and predictions.

The team's technical approach is based on using environmental probability density functions as estimates of environmental uncertainty, to provide a probabilistic measure of sonar performance. The approach specifically considered meso-scale fronts and eddies, tides, internal waves, interference variability in ambient noise and reverberation, and spatially variable bottoms.

[9] http://www.onr.navy.mil/sci_tech/ocean/321_sensing/cuwg/default.asp

3.1.1 Results

The UNITES team's uncertainty methodology uses probabilistic performance prediction for the end-to-end system. This methodology is mandated by the "present inability to predict acoustics deterministically due to the often unknown aspects of the ocean state (including the bottom)." The product of this methodology is called the predictive probability of detection (PPD).

The PPD is controlled by (at least) three parameters; the system mean transmission loss (TL), the system standard deviation of TL, and the local slope of the TL curve. The team found that the TL mean is determined primarily by the macro-state of the ocean and the bottom, and that the other two parameters are primarily determined by the micro-state (temporal and/or spatial "graininess") of the ocean. Members of the UNITES team have been working to transition the use of the probabilistic methodology into various practical applications including improved performance prediction and reducing uncertainty in ocean surveys.

The UNITES team's operational efforts led to a study of a passive broadband sonar system and an operation in the East China Sea (ECS). Using the PPD methodology mentioned above, the team was able to create a reasonable representation of the sonar/target system. They also generated ocean and acoustic uncertainty maps for the ECS and the New York Bite. These demonstrations have led to follow-on studies with the US Fleet.

The team has shown that "in a shallow water environment, probabilistic measurements that supplement propagation and environmental models (i.e. data assimilation), rather than models alone, are necessary for competent sonar performance predictions." Studies of data assimilation with physical-acoustical coupling applied to the PRIMER measured data show effective reduction of uncertainty in the mean TL.

The UNITES team has also quantified temporal and spatial variability in the environment and in transmission loss measured in the SWARM, PRIMER, and ASIAEX experiments. The propagation of uncertainty from the environment to the measured transmission loss has been analyzed, with emphasis on the water column sound speed variability. The sensitivity of mean TL to ocean sound speed estimate resolution was examined (when limited by mesoscale variability). The optimum resolution was found to be 20 m in vertical and 4 km in the horizontal.

Interim reports (in the form of presentations) from several of the UNITES sub-teams are also available from the Uncertainty DRI, including:

- Pat Gallacher, Steve Piacsek and M. Schaferkotter, NRL: *The Impact on the Sound Field of Internal Bores and Large Amplitude Internal Waves in the Continental Shelf/Slope Region*. Used the Navy Coastal Ocean Model (NCOM) to study reaction to currents, internal waves and sound speed changes. Transition product: Cluster analysis to group sound speed profiles for MODES database.

- Glen Gawarkiewicz and Chris Linder, WHOI, and Maureen Taylor, NMFS: *Climatological Approaches to Environmental Uncertainty in the Middle Atlantic Bight.* Discussed methods for collecting significantly greater amounts of climatological data and presenting it visually by a depth vs range color map of the sound speed with standard deviation shown as contour lines. This display is very easy to understand. Their conclusions are that the major changes to sound speed occur just over the shelf break. The dominant process in summer is frontal meandering; in winter it is wind forcing.
- Murray Levine, Oregon State Univ: *Capturing Uncertainty: Internal Waves.* Discussed the computer generation of a model for internal waves using random time and space phases in the Garrett-Munk wave height spectrum.
- J. Lynch, WHOI: *Uncertainty due to 3-D coastal oceanography with practical implications*. Found that internal waves 1) cause scattering of energy across modes affecting signal attenuation and impacting bottom inversion measurements; 2) fill in the shallow water noise notch; 3) change signal fluctuation levels, seeing 6-8 dB fluctuations in broadband signals due to internal wave ducting; 4) potentially cause correlation of noise and signals affecting signal processing schemes.

Other published results are described in more detail in the following sections.

3.1.2 Team Publications

A.R. Robinson, P.A. Abbot, P.F.J. Lermusiaux, and L. Dillman, "Transfer of uncertainties through physical-acoustical-sonar end-to-end systems: a conceptual basis," *Impact of Littoral Environmental Variability on Acoustic Predictions and Sonar Performance*, Ed. By Pace and Jensen, Kluwer Academic Publishers, 2002.

This is a description of the methodology and the framework used by the UNITES team during the Uncertainy DRI.

Abbot, P.A. and I. Dyer, "Sonar performance predictions based on environmental variability," in *Impact of Littoral Environmental Variability on Acoustic Predictions and Sonar Performance*, ed. by N. G. Pace and F. B. Jensen, Kluwer Academic Publishers, The Netherlands, 2002.

This paper describes the conceptual basis of the predictive probability of detection.

Abbot, P.A., S. Celuzza, I. Dyer, B. Gomes, J. Fulford, and J.F. Lynch (2003), "Effects of East China Sea shallow water environment on acoustic propagation," *IEEE J. Ocean. Eng*. **28** (2), 192-211.

The paper describes results from a 1997 experiment in the East China Sea. High-resolution measurements from CTDs and bathy-thermographs characterized the spatial and temporal variability in the shallow-water environment. Transmission loss was measured using explosive sources. The authors use the range-dependent OASES model to assess the relative contribution of different environmental parameters to the variability in the observed TL. The experimental results support the conclusion that the observed variation in TL was primarily due to unknown spatial variability of the bottom.

Lynch, J.F., A.E. Newhall, B. Sperry, G. Gawarkiewicz, A. Fredricks, P. Tyack, Ching-Sang Chiu, and P. Abbot (2003), "Spatial and temporal variations in acoustic propagation characteristics at the New England Shelfbreak front," *IEEE J. Ocean. Eng*., **28** (1), 129-150.

The authors study acoustic variability across the New Jersey shelf. High spatial resolution environmental (water column) data from the PRIMER experiment (1996-97) are used as inputs for the RAM PE model. Spatial sampling and temporal (seasonal and diurnal) variations are studied. Model results are compared to point-to-point range measurements.

Duda, T., J.F. Lynch, A.E. Newhall, Lixin Wu, and Ching-Sang Chiu (2004). "Fluctuation of 400 Hz sound intensity in the 2001 ASIAEX South China Sea Experiment," *IEEE J. Ocean. Eng*, **29** (4), 1264-1279.

The ASIAEX[10] experiment was a joint physical oceanography / ocean acoustics program. A suite of moorings measured time series of temperature, conductivity, and current velocity throughout the water column near a shelf-edge site in the South China Sea (SCS). Two weeks of measurements were obtained. This paper examines the intensity fluctuations of received acoustic data for a broadband 400 Hz signal. Temporal variations in the received signal are observed at timescales ranging from seconds to days. The fluctuations are linked to weather events, tides, and internal solitons.

Chiu, Ching-Sang, S.R. Ramp, J.H. Miller, J.F. Lynch, T. Duda, and Tswen Yung Tang (2004). "Acoustic intensity fluctuations induced by South China Sea internal tides and solitons," *IEEE J. Ocean. Eng*, **29** (4), 1249-1263.

This paper presents results from the ASIAEX project (see above). The authors of this paper compare fluctuations to acoustic intensity to fluctuations in water column properties. A coupled normal mode model and the measured sound speed profiles are used to predict received acoustic intensity, and the results compared to measurements. The environmental measurements a Robert C. re made with a spatial resolution on the order of 10 m and a temporal resolution of 30 minutes. Two different scenarios are considered; one where sound speed variations are dominated by internal solitons, and one where sound speed variations are dominated by internal tides.

Gawarkiewicz, G., K.H. Brink, F. Bahr, R.C. Beardsley, M. Caruso J.F. Lynch, and C. Chiu (2004), "A large-amplitude meander of the shelfbreak front during summer south of New England: Observations from the Shelfbreak PRIMER experiment," *J. Geophys. Res.* **109**.

The authors present measurements from the PRIMER experiment (1996) describing the spatial and temporal variability of the temperature, salinity, and velocity of the water column near the shelf.

Sperry, B., J.F. Lynch, G. Gawarkiewicz, Ching-Sang Chiu, and A. Newhall (2003), "Characteristics of acoustic propagation to the eastern vertical line array receiver during the summer 1996 Shelfbreak PRIMER experiment," *IEEE J. Oceanic Eng.* **28** (4), 729-749.

The authors consider environmental and acoustic measurements from the PRIMER experiment, using a PE model and normal modes to analyze the effect of temporal and

[10] http://www.apl.washington.edu/programs/ASIAEX/index.html

spatial variability on the acoustic measurements. The authors find that in the shelf region the oceanography (not the bottom) is the strongest contributor to range-dependent behaviour. They also find that the fine-scale oceanography must be treated in a fully three-dimensional sense when modeling coastal acoustic transmissions.

Fredricks, A., J. Colosi, J.F. Lynch, G. Gawarkiewicz, Ching-Sang Chiu, and P.A. Abbot (2005), "Analysis of multipath scintillations from long range acoustic transmissions on the New England continental slope and shelf," *J. Acoust. Soc. Am*. **117** (3), 1038-1057.

The authors report on intensity fluctuations of received acoustic data for a broadband 400 Hz signal during the PRIMER experiment in 1996. The received data are compared to results obtained using the RAM PE model. Note the similarities in subject matter between this paper and the Duda *et. al* (2004) paper above.

Lermusiaux, P.F.J., Ching-Sang Chiu, and A.R. Robinson (2002), "Modeling Uncertainties in the Prediction of the Acoustic Wavefield in a Shelfbreak Environment," *Proceedings of the 5th ICTCA*, May 21-25, 2001, in *Theoretical and Computational Acoustics 2001*, ed. by E.-C. Shang, Q. Li and T.F. Gao, World Scientific Publishing Co., 191-200.

Robinson, A.R. and P.F.J. Lermusiaux (2003), "Prediction Systems with Data Assimilation for Coupled Ocean Science and Ocean Acoustics," in *Proceedings of the Sixth International Conference on Theoretical and Computational Acoustics*, ed. by A. Tolstoy *et al.*, World Scientific Publishing, [In press].

These two papers give an overview of data assimilation as it can be applied to combine oceanographic and geophysical measurements with acoustic prediction. They both present an example of data assimilation using measurements from the PRIMER experiment.

3.2 Seabed Variability Team

The Seabed Variability and its Influence on Acoustic Prediction Uncertainty team of the Uncertainty DRI has been led by Charles Holland of ARL/PSU. The Seabed Variability team included a number of geophysicists interested in the root geological causes of seabed variability.

The Seabed Variability Team had two principle objectives: to assess seafloor variability in continental shelf environments; and to determine the impact of seafloor variability on acoustic prediction uncertainty. This team intentionally stopped short of an end-to-end approach to the uncertainty problem in order to specialize on the seabed variability aspect; their intent was to provide seafloor variability products to other teams addressing the oceanographic variability, signal processing and sensing/information dominance issues.

3.2.1 Results

Several interim reports (in the form of presentations) from the Seabed Variability sub-teams are available from the Uncertainty DRI, including:

- Brian Calder and Larry Mayer, Center for Coastal and Ocean Mapping and NOAA-Univ. New Hampshire Joint Hydrographic Center: *Bathymetric Uncertainty Assessment*. Developed quadratic relation for uncertainty standard deviation in bathymetric reconstructions using high-resolution data. Also examined uncertainty in sparse and archive datasets. Suggest producing uncertainty maps showing measurement and processing uncertainty.
- John Goff, University of Texas Institute for Geophysics, and contributors B. Kraft, L. Mayer, S. Schock, S. Gulick, H. Olson, S. Nordfjord, C. Sommerfield, H. Lee, R. Wheatcroft, D. Drake, D. Swift and S. Fan: *Spatial Variability of Seafloor Sediment Properties*. Sought a statistical model of variability that can be used to make Monte Carlo realizations of sediment properties in unsampled areas. The assumption is that the variability is tied to geologic processes. Sought to correlate remotely sensed data (backscatter and seismic reflection data) to seabed properties. Found backscatter displays an inverse correlation with grain size and velocity and sorting it out requires ground truth. Also examined a relationship between grain size and velocity.
- Charles Holland, Stan Dosso, C. Harrison, B. Kraft, K. LePage, I Overeem, L. Pratson, and J. Syvitski: *Seabed Variability and Uncertainty Characterization*. Examine geoacoustic measurements from two different regions of the mediterranean. Conclude that intra-regional variability is a high percentage of worldwide estimates (Hamilton): velocity = 80%, density = 90%, attenuation = 30% of world wide estimate. Conversely there is remarkable similarity between regions 800 km apart. This similarity may be predictable by using a geologic model of sedimentation processes.
- P. Gerstoft, C. Huang, and W. Hodgkiss, MPL/ Scripps: *Geoacoustic Inversion and Uncertainty Mapping*. Inverted propagation loss data using marginal posterior probability technique for bottom parameters of speed, attenuation, water depth. The statistical properties of TL can be estimated based on the output from the inversion using a likelihood method.
- B. Kraft, L. Mayer, L. Pratson, C. Holland, and I. Overseem: *Comparing Sedflux Predictions to Geoacoustic Data*. Demonstrated success using a geologic model (Sedflux) to predict similar properties from two widely separated regions. Showed relationships between geologic processes and sediment properties. Sedflux maps grain size into empirical models for porosity, bulk density and permeability. These are used in the Buckingham or EDFM models for compressional velocity.
- R. Odom and A. Ganse, APL/UW: *Resolution, Variance and Seabed Variability*. Used partial derivatives (Frechet) of acoustic pressure with respect to bulk modulus and density, which can be obtained by iteration of SAFARI or FFP or analytically for a simplified case. Then the matrix of resolutions was formed. Employed over-resolved (more data than variables) matrix solution and forward modeling to invert data for bottom loss and

bottom scattering strength. Variability appears as Gaussian distribution of grain sizes and sediment thickness which produces histograms of BL and BSS.

Other published team results are referenced and briefly described in the following section. A full publication list has been obtained from the Seabed Variability team final report.

3.2.2 Team Publications

Calder, B.R. (2004), "On the Uncertainty of Archive Hydrographic Datasets," *Proc. Canadian Hydro. Conf.*, Ottawa, Canada.

The author undertakes a comparison between a modern MBES survey of a region of the New Jersey shelf and two archival (NOAA) surveys of the same area; a leadline survey from 1936-38, and a VBES survey from 1975-76. The analysis shows that the leadline survey is heavily biased in deeper water and probably useless, but that the VBES data are unbiased and may be useful. The paper also considers uncertainty in a surface model constructed from the sparse archival survey.
Note that a paper with a similar title has been submitted to IEEE J. Oceanic Engr. (see section 4.1).

Jakobsson, M., Calder, B., Mayer, L., and Armstrong, A. (2002), "On the Effect of Random Errors in Gridded Bathymetric Compilations," *J Geophys. Res. B (Solid Earth)* **107** (B12), ETG 14-1 – 14-11.

Address the propagation of uncertainty from bathymetric measurements through construction of a regularly-spaced grid.

Jenkins, C.J., 2004, "Quantifying the Uncertainty in Marine Substrate Mappings," *Continental Shelf Res.*, in review

Discussed USGS and Univ of Colorado data base (INSTAAR) of US and global seabed grain sizes.
See also Chris Jenkins, World Seabed Data Browser[11]

Goff, J.A., B.J. Kraft, L.A. Mayer, S.G. Schock, C.K. Sommerfield, H.C. Olson, S.P.S. Gulick, and S. Nordfjord (2004), "Seabed characterization on the New Jersey middle and outer shelf: Correlability and spatial variability of seafloor sediment properties," *Mar. Geol.* **209**, 147-172.

Describe a comparison between geologic samples and remotely-sensed bottom measurements for an area of the New Jersey shelf.

Holland, C., "Intra and inter-regional geoacoustic variability in the littoral" in *Impact of Littoral Environmental Variability on Acoustic Predictions and Sonar Performance*, eds. N. Pace and F. Jensen, Kluwer Academic Publishers, 2002.

The author looks at the question of how geoacoustic parameters vary in the region near (~1000 m) a measurement (intra-regional variability), and whether they can be extrapolated to points that are far (~100,000 m) from a measurement point (inter-regional variability).

[11] http://instaar.colorado.edu/~jenkinsc/dbseabed/goseabed/interactive/

Mayer, L.A., B.J. Kraft, P. Simpkin, P. Lavoie, E. Jabs, and E. Lynskey, "In-situ determination of the variability of seafloor acoustic properties: an example from the ONR GEOCLUTTER area," in *Impact of Littoral Environmental Variability on Acoustic Predictions and Sonar Performance*, ed. by N. G. Pace and F. B. Jensen, Kluwer Academic Publishers, 2002.

Overeem, I., J.P.M. Syvitski, E.W.H. Hutton, A.J. Kettner (2003), "Stratigraphic variability due to uncertainty in model boundary conditions: a case-study of the New Jersey Shelf over the last 21,000 years," *Marine Geology* [submitted]

Syvitski and others have published several results showing that a model of geologic processes (climatology, sea level, etc.) can predict sea floor sediment composition and structure. The model boundary conditions referred to here are the global forces that drive sedimentation. The geological model is SedFlux.

Holland, C. (2003), "Seabed reflection measurement uncertainty," *J. Acoust. Soc. Am.* **114**, 1861-1873.

Derived techniques for estimating the amplitude and angle uncertainties based on measurement techniques. Typical uncertainty is ±0.5 to 1.5 dB and ±0.1 to 0.3 degrees grazing.

Holland, C.W., "High resolution geoacoustic measurements on the New Jersey and Scotian Shelf" in *Proceedings of Geoclutter and Boundary Characterization 2001: Acoustic Interaction with the Seabed*, eds. P. C. Hines, N. C. Makris, and C. W. Holland DREA, Defence Research Establishment Atlantic, Technical Memorandum DREA TM 2001-185, 2001.

This paper gives an overview of seafloor and scattering measurements from two experiments.

Holland, C.W. (2002), "Shallow water coupled scattering and reflection measurements," *IEEE J. Ocean. Eng.*, **27** (3), 454-470.

This paper presents results from scattering and reflection measurements made on the Malta plateau, for 1-6 kHz signals. Despite a relatively uniform bottom, the reflection and scattering measurements showed significant spatial variability. The author concludes that this is because the processes are dominated by sediment properties below the surface-sediment interface, and singles out the sediment layer thickness.

Holland C.W., J. Dettmer, and S. E. Dosso (2005), "Remote sensing of sediment density and velocity gradients in the transition layer," *J. Acoust. Soc. Am.* **118** (1)*,* 163-177.

The authors show that broadband seabed reflection data can be exploited to obtain the depth dependent density and velocity profiles in the transition layer to high accuracy. A Bayesian inversion approach, which accounts for correlated data errors, provides estimates and uncertainties for the geoacoustic properties. These properties agree with direct (core) measurements within the uncertainty estimates.

Dosso S., C. Holland, "Bayesian Inversion of Seabed Reflection Data," in *2nd Workshop on Experimental Acoustic Inversion Methods for Assessment of the Shallow Water Environment*, Ischia, Italy, (2004) Studied mathematics of the transfer of uncertainty from the reflection coefficient to Geoacoustic parameters using Bayesian mathematics.

LePage, K.D., "Modeling propagation and reverberation sensitivity to oceanographic and seabed variability," In *Impact of Littoral Environmental Variability on Acoustic Predictions and Sonar Performance*, eds. N. G. Pace, and F. B. Jensen, Kluwer, The Netherlands, 2002.

The author analyzes the propagation of oceanographic and bottom uncertainty through an adiabatic normal mode model. The waveguide variability is characterized as a Gaussian-distributed process parameterized using second-order statistics and a correlation length scale. Using the closed-form solutions, the author then used Monte Carlo simulation and multiple model runs for a shallow-water (140m) downward-refracting environment with a two-layer bottom, and a narrowband 500 Hz source.

The author conludes that for propagating signals, early arrivals are most sensitive to variability in the sound speed (internal waves), whereas late arrivals are most sensitive to variability in bottom properties (sound speed and attenuation). There are also preliminary results presented for reverberation.

Note that this work is reproduced in SACLANTCEN Memorandum SM-398.

Holland, C., S. Dosso, and J. Dettmer, "A technique for measuring in-situ compressional wave velocity dispersion in marine sediments," *IEEE J. Oceanic Eng*, in press.

The authors studied velocity dispersion in unconsolidated sediments and found uncertainty of ±5.0m/s, which was surprisingly small.

Odom, R. (2003), "Frechet derivatives for shallow water ocean acoustic inverse problems," *J. Acoust. Soc. Am.* **113**, 2191.

Used partial derivatives (Frechet) of acoustic pressure with respect to bulk modulus and density, which can be obtained by iteration of SAFARI or FFP or analytically for a simplified case. Then the matrix of resolutions was formed. Employed over-resolved (more data than variables) matrix solution and forward modeling to invert data for bottom loss and bottom scattering strength. Variability appears as Gaussian distribution of grain sizes and sediment thickness which produces histograms of BL and BSS.

LePage, K.D. and B.E. McDonald, "Environmental effects of waveguide uncertainty on coherent aspects of propagation, scattering and reverberation," in *Proceedings of the High Frequency Conf.*, La Jolla, CA, 1-5 March, 2004. AIP Press, New York

The authors use normal mode theory and narrowband approximation to examine signal coherence in the presence of environmental uncertainty, including water and bottom sound speed perturbations and bathymetry changes.

LePage, K.D. (2001), "Acoustic time series variability and time reversal mirror defocusing due to cumulative effects of water column variability," *J. Comp. Acoust.* **9**, 1455-1474.

The author considers the variability of the received time series for a narrowband signal in a fluctuating ocean waveguide. Expressions are derived for the expected value of the signal intensity as a function of sound speed variability.

Lepage, K.D., Holland, C., and Goff, J.A. (2003), "Transfer of oceanographic and bottom variability into shallow water propagation and reverberation uncertainty," *J. Acoust. Soc. Am.* **114** (4), 2311-2312.

The authors discuss spatial resolution of environmental measurements and propose that global variability can be statistically estimated by sampling a limited area at high resolution. Using Monte Carlo techniques, the authors estimate the sensitivity of reverberation and propagation measurements to fine-scale sound speed and sea floor variability at the STRATAFORM sites. Uncertainty in reverberation is estimated as about 1 dB at 4 kHz, and uncertainty in propagation loss is estimated as about 2 dB.

3.3 Propagation of Uncertainty Team

The Modeling and Analyzing the Propagation of Uncertainty From the Environment Through Sonar Performance Prediction team has been led by William Kuperman of SIO-UCSD. We were unable to obtain a 2005 report from the Kuperman team. The following is extracted from their 2004 report.

The Propagation of Uncertainty team had three long-term goals: to understand the propagation of uncertainty from the ocean environment to performance prediction; to develop a simulation platform for the purpose of understanding this propagation; and to develop a methodology to distill the complex uncertainty and sensitivity into relevant situational awareness for sonar operators.

3.3.1 Results

The team used simulation and theory, as well as real data, in approaching the problem. The team had two principle thrusts. The first was the development of an acoustic adjoint methodology, which enables a quasi-analytic estimate of acoustic observable sensitivity to environmental perturbations. The second was the study of a Bayesian approach to sonar performance prediction.

Some published team results are referenced and briefly described in the following section.

3.3.2 Team Publications

Thode, A. (2004), "The derivative of a waveguide acoustic field with respect to a three-dimensional sound speed perturbation," J. Acoust. Soc. Am. **115** (6), 2824-2833.

The authors derive expressions for the first-order "environment derivative" of a pressure field in a range-independent waveguide, with respect to an arbitrary three-dimensional sound speed perturbation in either the water column or the sediment. The derivative is computed using an adjoint Green's function method. In restrictive geometry of the waveguide allows the integrals required in the adjoint method to be simplified. The derived expressions are demonstrated with a sensitivity study of horizontal refraction due to different sound speed perturbations. The paper concludes by stating that the environmental derivative expressions could be used for estimating the sensitivity of an acoustic field to a perturbation.

Thode, A., and K. Kim (2004), "Multiple-order derivatives of a waveguide acoustic field with respect to sonud speed, density, and frequency," J. Acoust. Soc. Am. **116** (6), 3370-3383.

This paper is an extension of the previous in which first-, second-, and third-order derivatives are calculated with respect to sound speed, density, and frequency. As before the geometry is restricted to the range-independent waveguide. The results are used to examine the question of when acoustic mode *amplitude* changes can be neglected when assessing the impact of environmental perturbations. The results suggest that the derivatives of normal mode amplitudes with respect to bottom parameters are non-negligible.

Hursky, P, M.B. Porter, B.D. Cornuelle, W.S. Hodgkiss, W.A. Kuperman (2004), "Adjoint modeling for acoustic inversion," J. Acoust. Soc. Am. **115,** 607-619.

This paper addresses the use of adjoint-method derivatives to acoustic inversions.

Sha, Liewei and L.W. Nolte, "Detection performance prediction in uncertain ocean environments: Bayesian viewpoints," *J. Acoust. Soc. Am.*, revision submitted April 2004.

Sha, Liewei and L.W. Nolte, "Effects of environmental uncertainties on sonar detection performance prediction," *J. Acoust. Soc. Am.* **117** (4), 1942-1953.

Note: it is not clear if the two above articles are the same article.

The authors propose a Bayesian (statistical decision theory) approach to estimating sonar performance, because it can directly incorporate environmental uncertainty and therefore give more realistic performance estimates than the classic sonar equation. The authors derive analytical ROC curves using this approach and show that the performance depends primarily on the received signal-to-noise ratio and the environmental uncertainty, which is captured in the rank of the signal matrix.

Another result demonstrates that even the optimal Bayesian detector needs to accurately know the statistical characteristics of the uncertainty, or performance will be degraded.

Sha, Liewei, and L.W. Nolte (2005), "Bayesian sonar detection performance prediction in the presence of interference in uncertain environments," *J. Acoust. Soc. Am.* **117** (4), 1954-1964.

The authors develop closed-form expressions for the ROC curve of the Bayesian detector in the presence of interference and environmental uncertainty. One of the conclusions is that the degradation on detection performance due to interference is greatly magnified by the presence of environmental uncertainty.

Book, P., J. L. Krolik, and S. Kraut (2003), "Adaptive sonar detection performance prediction in an uncertain ocean," *J. Acoust. Soc. Am.* **113** (4), 2263.

This paper addresses the problem of predicting detection performance of an adaptive beamformer (DT calculation) when the signal wavefront is uncertain and the noise field directionality is unknown. Both of the input uncertainties originate from enviromental uncertainty, although this paper addresses propagation of uncertainty through the sonar system. Note also the following more recent paper:

J. L. Krolik, P. Book, S. Kraut, "In situ detection performance assessment of a sonar array when the signal wavefront and noise covariance are uncertain," in *Proc.*

of Sensor Array and Multichannel Signal Processing Workshop, Barcelona, July 2004 (in press).

3.4 Statistical Properties Team

The Statistical Properties of the Acoustic Field in Inhomogeneous Oceanic Environments team of the Uncertainty DRI was led by Oleg Godin and Alexander Voronovich of the NOAA. All of the published papers were authored by one or both of these researchers, with additional contribution from Iosif Fuks.

3.4.1 Results

The work of the Statistical Properties team is highly analytical in nature. The primary environmental perturbations considered have been moving fluids (currents), three-dimensional inhomogeneities (e.g. horizontal refraction), and temporal fluctuations. The team's work could be summarized as a numerical and analytical study of the statistical properties of the acoustic field in an ocean with these variations superimposed on a range-dependent, deterministic background. The focus of the research was to develop mathematical models which translate uncertainty in (or purely statistical information about) environmental parameters into uncertainty (or statistical characteristics) of various acoustic observables of interest.

Some of the team's results are briefly summarized in the following section.

3.4.2 Team Publications

Godin, O.A. (2002), "Coupled-mode sound propagation in a range-dependent, moving fluid," *J. Acoust. Soc. Am*. **111**, 1984-1995.

New and improved techniques have been put forward to incorporate data on oceanic currents into acoustic propagation models based on a coupled-mode representation of the field and a wide-angle, energy-conserving, 3-D parabolic approximation. This team has published a number of papers on this topic.

Godin, O.A. (2002), "On effective quiescent medium for sound propagating through an inhomogeneous, moving fluid," *J. Acoust. Soc. Am*. **112**, 1269-1275.

The authors have published several papers on the "effective sound speed" approximation for dealing with currents in acoustic models.

Godin, O.A., "Random horizontal refraction and biases in ray travel time and mode phase," in *Proceedings of the Sixth European Conference on Underwater Acoustics (24-27 June 2002, Gdansk, Poland)*, Gdansk University of Technology, Gdansk, 2002.

Travel-time biases associated with sound refraction and scattering by unresolved inhomogeneities have been found to have important implications for various acoustic remote sensing techniques ranging from echosounding to ocean acoustic thermometry and tomography. See also:

Godin, O.A. (2002), "A 2-D description of sound propagation in a horizontally-inhomogeneous ocean," *J. Comput. Acoustics* **10**, 123-151.

The authors consider the decoupled azimuth approximation commonly used in acoustic modelling and consider the error that arises in a three-dimensional ocean. They make recommendations on reliability of predictions obtained assuming range-dependent ocean and disregarding horizontal refraction and effects due to ocean currents and time-dependence of the environmental parameters in deep and shallow water. See also [abstract only]:

Godin, O.A. (2000), "Travel Time bias in 2D modeling of 3D sound propagation," *J. Acoust. Soc. Am.* **107** (5), 2808.

Godin, O.A., I.M. Fuks, and M.I. Charnotskii (2005), "Backscattering of short acoustic pulses from 3-D rough surfaces: Statistical properties of first arrivals," *J. Acoust. Soc. Am.* **117** (4), 2434.

The authors consider the statistical properties of backscattered waves, using the geometrical acoustic approximation. Predictions of an asymptotic theory are verified against numerical simulation. The uncertainty in the travel time and received intensity are quantified. The work is an extension of:

Fuks, I.M., and O.A. Godin (2004), "Probability distribution of the travel time and intensity of the two first arrivals of a short pulse backscattered by a rough surface," *Waves in Random Media* **14**, 539-562.

4. Other Recent Literature

Simons, D.G., R. McHugh, M. Snellen, N.H. McCormick, and E.A. Lawson (2001), "Analysis of Shallow-Water Experimental Acoustic Data Including a Comparison With a Broad-Band Normal-Mode-Propagation Model," *IEEE J. Ocean. Eng.* **26** (3), 308.

[Research carried out as part of the MAST III project PROSIM[12]. PROSIM is a propagation channel simulation model. It aims to provide accurate shallow-water predictions of broadband acoustic propagation in the 400 Hz to 15 kHz band. It includes both deterministic and stochastic acoustic propagation effects.] The paper describes experiments off Scotland in 1997, including a characterization of variability in the transmission loss and in the environment.

Chapman, D.M.F. and Kessel, R.T., "Uncertainty and Variability in Ocean Acoustics: How Do We Cope?" in *Acoustics 2002 – Innovation and Vibration*, 13-15 November 2002, Adelaide, Australia, 2002.

The authors use adiabatic mode theory in a weakly range-dependent environment to study a shallow-water Pekeris environment with a specified uncertainty (error in estimated parameters) and variability (random variation of parameters). By expanding the range-dependent wavenumber to second order in the model parameters, the authors are able to show that the sensitivity to the uncertainty is determined by the first derivatives of the wavenumber with respect to the parameters, and the sensitivity to the variability is determined by the second derivatives (including cross-derivatives).

The authors proceed to demonstrate a specific case where the effect of a random variation in the bottom depth on the transmission loss is indistinguishible from the effect of a uniform change in the water depth.

This work is an extension of:

Kessel, R.T., "Range-dependent environmental mismatch in Matched-Field Tomography," *Proceedings of the Joint Meeting of the 16th Int. Congress on Acoustics and the 137th Meeting of the Acoustical Society of America*, Seattle, WA, June 1998.

An abstract appears in *J. Acoust. Soc. Am.* **103** (5), 2936.

Kessel, R.T. (1999), "A mode-based measure of field sensitivity to geoacoustic parameters in weakly range-dependent environments," *J. Acoust. Soc. Am.*, **105**, 122–129.

The author sets out to formulate a new measure of sensitivity. An average over source-receiver geometry is obtained directly from adiabatic-mode theory, by focusing on the horizontal phase of the modes. The author presents examples of sensitivity estimates for the P- and S-wave speeds in the bottom, range-dependent bathymetry, and other geoacoustic parameters, including the frequency-dependence of sensitivity. For a particular environment (Western Bank) the field was found to be most sensitive to the sediment compressional sound speed and the bathymetry.

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[12] http://www.saclantc.nato.int/mast/prosim/mainpg/main.html

Kessel, R.T. (1997), "The variation of modal wave numbers with geoacoustic parameters in layered media," *J. Acoust. Soc. Am.*, **102**, 2690–2696.

The author constructs analytic derivatives of acoustic normal modes in a layered environment, with respect to the compressional wave speed, shear wave speed, density, thickness, and depth of any layer. This work is complementary to the 1999 paper described above.

Williams, K.L., D.R. Jackson, E.I. Thoros, D. Tang, and K.B. Briggs (2002), "Acoustic Backscattering Experiments in a Well Characterized Sand Sediment: Data/Model Comparisons Using Sediment Fluid and Biot Models," *IEEE J. Ocean. Eng.* **27** (3), 376-387.

The authors compare measured backscattering from the SAX99 experiment to three different sediment models; a mess density fluid model, a poroelastic model based on Biot theory, and an effective density fluid model based on Biot theory. The measurement frequency range (20-300 kHz) is outside the range of interest specified for this study.

Thorsos, E.I., et. al (2001), "An Overview of SAX99: Acoustic Measurements," *IEEE J. Ocean. Eng.* **26** (1), 4-25.

Richardson, M.D., et. al (2001), "Overview of SAX99: Environmental Considerations," *IEEE J. Ocean. Eng.* **26** (1), 26-53.

The SAX99 experiment in the Gulf of Mexico addressed high-frequency (10-300 kHz) acoustic backscatter from, absorption by, and propagation in the seafloor. These two papers give an overview of the SAX99 measurement program, which used an extensive collection of different instruments, and present some preliminary results.

Mu, Y., M. Badiey, W.L. Siegmann, S. Frank, J.F. Lynch, S.N. Wolf (2000), "Analysis of internal wave interactions with broadband acoustic signals propagating along the shelf during the SWARM'95 experiment," *J. Acoust. Soc. Am.* **107** (5), 2830.

The authors present temporal variability of received signal intensity due to internal waves during the SWARM'95 experiment.

Richardson, M.D., and Briggs, K.B., "Empirical Predictions of Seafloor Properties Based on Remotely Measured Sediment Impedance," in *High Frequency Ocean Acoustics*, proceedings of the High Frequency Ocean Acoustics Conference, La Jolla, USA, 2004, pp 12-21.

The paper presents regressions that allow various geoacoustic properties to be predicted from an impedance index. The results are based on a large number of sample cores (most from the upper 30 cm) from 67 shallow water sites around the world. These samples provide a representation of global geoacoustic variability.

Jackson, D.R., "Progress and research Issues in High Frequency Seafloor Scattering," in *High Frequency Ocean Acoustics*, proceedings of the High Frequency Ocean Acoustics Conference, La Jolla, USA, 2004, pp 125-131.

This article reviews the status of model-data comparisons for seafloor scattering. The author argues that interfacial scattering is relatively well understood, but scattering within the sediment is not.

Porter, M.B., et. al, “The Kauai Experiment,” in *High Frequency Ocean Acoustics*, proceedings of the High Frequency Ocean Acoustics Conference, La Jolla, USA, 2004, pp 307-321.

An overview of and preliminary results from the Kauai experiment (2003), which collected acoustic measurements in the 8-50 kHz range, and environmental measurements to characterize temporal and spatial variability. One of the stated goals of the project was to better understand forward-scattered waves at these frequencies.

Gauss, R.C., and R. Soukup, “Measurements of Time Spread on the New Jersey Shelf Using Time-forward and Time reversed Signals,” in *Proceedings of Geoclutter and Boundary Characterization 2001: Acoustic Interaction with the Seabed*, eds. P. C. Hines, N. C. Makris, and C. W. Holland DREA, Defence Research Establishment Atlantic, Technical Memorandum DREA TM 2001-185, 2001.

The authors present mid-frequency shallow water propagation measurements and use them to extract measures of time spread and signal coherence.

Gauss, R.C., and R. Soukup, “Measurements of Time Spread on the New Jersey Shelf Using Time-forward and Time reversed Signals,” in *Proceedings of Geoclutter and Boundary Characterization 2001: Acoustic Interaction with the Seabed*, eds. P. C. Hines, N. C. Makris, and C. W. Holland DREA, Defence Research Establishment Atlantic, Technical Memorandum DREA TM 2001-185, 2001.

The authors present mid-frequency shallow water propagation measurements and use them to extract measures of time spread and signal coherence.

Kunz, E.L., “Measurements of Mid-frequency Scattering Strengths on the New Jersey Shelf,” in *Proceedings of Geoclutter and Boundary Characterization 2001: Acoustic Interaction with the Seabed*, eds. P. C. Hines, N. C. Makris, and C. W. Holland DREA, Defence Research Establishment Atlantic, Technical Memorandum DREA TM 2001-185, 2001.

This paper presents an empirical determination of scattering strength and characteristics of the PDF of bottom interaction in several zones.

Tollefsen, D., “Estimates of sediment geoacoustic parameters in the Barents Sea by inversion of horizontal line array data,” in *Proceedings of the International Conference on Underwater Acoustic Measurements, Technologies and Results*, Heraklion, Crete, 2005, p. 637.

The author presents values for sediment parameters, and errors, estimated from a matched field inversion using explosive sources.

Nielsen, P.L., M. Fallat, S. Dosso, and M. Siderius, “Measurements of Weakly Varying Geoacoustic Properties and their impact on Acoustic Propagation,” in *Proceedings of the International Conference on Underwater Acoustic Measurements, Technologies and Results*, Heraklion, Crete, 2005, p. 657.

The authors present inversion results from an experiment near Malta. The results demonstrate that horizontal array inversions provide sufficient bottom information for excellent propagation prediction.

Other interesting measurements are presented in the Crete 2005 proceedings, notably in Structured Session 13, “Underwater Acoustic Measurements in the Baltic Sea Past, Present, and Future” (papers by Poikonen, Klusek, and Gerdes) and in Structured Session 6, “Acoustics in Coastal Sediments: Measurement Techniques as a Function of Frequency and Temporal Scales.”

4.1 *IEEE J. Ocean. Engr.* Special Issue

In 2004 the IEEE issued a call for papers for a special issue of the *IEEE Journal of Oceanic Engineering*, focusing on environmental uncertainty and its effect on sonar performance predictions. At the time of the initial announcement, the special issue was scheduled for January of 2005, but it was not published at that time.

When the special issue is published, it will likely contain some papers that are of interest for this project. Based on the reports from the Uncertainty DRI, we can identify the following articles that have been submitted for publication to but not yet published in *IEEE J. Ocean. Eng.* It is not clear that all of these have been accepted for the special issue.

Abbot, P.A., I. Dyer, and Emerson, “Stochastics of Transmission Loss in the Shallow East China Sea”

Abbot, P.A., Ching-Sang Chiu, and J.F. Lynch, “Acoustic Signal and Noise Level Variability Measurements From 1996 Summer Shelfbreak PRIMER Tests”

Calder, B.R., “On the Uncertainty of Archive Hydrographic Datasets.”

Chiu, Ching-Sang et al., “Bandwidth dependence of shelf-slope TL statistics.”

Dosso, S. E. and C. W. Holland, “Geoacoustic uncertainties from viscoelastic inversion of seabed reflection data.”

Fredricks, A., J.A. Colosi, and J.F. Lynch, “Analysis of multipath scintillations observed during the summer 1996 New England shelfbreak PRIMER study.”

Fulford, J., “Estimate of Uncertainty in Acoustic Propagation adjacent to the Strait of Korea

Gerstoft, P., C-F. Huang, and W.S. Hodgkiss, “Posterior estimation of transmission loss from ocean acoustic data.”

Godin, O.A., V.U. Zavorotny, A.G. Voronovich, and V.V. Goncharov, “Refraction of sound in a horizontally-inhomogeneous, time-dependent ocean.”

Heaney, K, and H. Cox, “A tactical approach to environmental uncertainty and sensitivity.”

Heaney and Cox made a presentation to the Uncertainty DRI that formed the basis for this paper. Using a combination of measurements, inversions, and modeling, the authors can communicate the instantaneous and time-averaged uncertainty in detection range predictions. In the environment under study (Mediterranean from BOUNDARY 2003), the SVP and geoacoustic variability is on the order of 0.5 dB, and detection range variability it on the order of 800 m at 7000 m.

Holland, C.W., R. Gauss, P. Hines, P. Nielsen, D. Ellis, J. Preston, K.D. LePage, C. Harrison, J. Osler, R. Nero and D. Hutt, "Boundary Characterization Experiment Series Overview."

Kraft, B.J., I. Overeem, C.W. Holland, L.F. Pratson, J.P.M. Syvitski, and L.A. Mayer, "Stratigraphic model predictions of geoacoustic properties."

Krolik, J.L., P. Book, and S. Kraut, "In Situ Adaptive CFAR Performance Assessment for Passive Sonar."

Lermusiaux, P.F.J., Ching-Sang Chiu et al., "Four-Dimensional data assimilation for coupled physical-acoustical fields: Application to Shelfbreak PRIMER data."

LePage, K.D., "Modeling propagation and reverberation sensitivity to oceanographic and seabed variability."

LePage, K.D. and B.E. McDonald, "Environmental effects of waveguide uncertainty on coherent aspects of propagation, scattering and reverberation."

Lin, Chen, and J.F. Lynch, "An equivalent transform method for evaluating the effect of the water column mismatch on geoacoustic inversion."

Linder, C., G. Gawarkiewicz, and M. Taylor, "Climatological estimation of environmental uncertainty over the Middle Atlantic Bight shelf and slope."

Odom, R.I. and G.M. Anderson, "Model and data resolution for ocean acoustic for ocean seabed inverse problems."

Sha, Liewei, and L.W. Nolte, "Bayesian sonar detection performance prediction with SWellEX96 vertical array data."

Sha, Liewei, and L.W. Nolte, "Localization performance prediction in uncertain ocean environments; Bayesian viewpoint and analytical approximations."

5. Overview of Suggested Acoustic Models

As part of the phase I activity, the scientific authority provided the project team with a suggested set of acoustic models. This section summarizes the main features and limitations of these models, and the inputs that each model requires, in light of how they might be applied in phases II and III.

5.1 KRAKEN

KRAKEN is a normal mode propagation model.

5.1.1 Features

- Multilayered environments including stratified elastic layers
- Includes interfacial roughness at each layer boundary
- Option to supply tabulated surface and bottom reflection coefficients
- Boundary condition options: free, rigid, and homogeneous half-space
- Can calculate full field (on requested range-depth grid) and/or field for multiple source depths
- Range-dependence / 3-D
- Can calculate range-dependent 2-D solutions using either coupled modes or adiabatic approximation
- Can calculate output on N×2-D grid, including horizontal refraction
- Can specify input on randomly- or regularly-spaced grid in three dimensions

5.1.2 Limitations

- Cannot calculate reverberation for active performance prediction
- Code uses a single frequency; multiple values require multiple runs.

5.1.3 Model Inputs

The environment may be specified at any number (possibly limited to ≤ 70?) of positions in the horizontal plane. All parameters, including depth, can vary with location. The specification format is identical at each location; modes are first calculated for each location, and the field is calculated by integrating the modes, interpolating between locations where inputs are specified. At any given location, the depth spacing does not have to be uniform and can be arbitrary. The following describes the specification for any given location.

There may be up to 20 media (layers). Note that this is in addition to the upper and bottom boundary layers which are treated as semi-infinite half-spaces. Normally one of these media would be the water column; however, in situations where the sound speed has abrupt jumps with depth it may be advisable to split the water column into multiple media.

For each medium, the **P-wave speed**, **S-wave speed**, **P-wave attenuation**, and **S-wave attenuation** may be specified as a function of depth. In addition, a **density** may be specified for each medium. Variations in density within a medium are ignored. Attenuation can be specified in several ways (Nepers/m, dB/km-Hz, dB/m, dB/wavelength, or a Thorpe model).

At every boundary between media, an RMS **interfacial roughness** may be specified.

The upper half-space may be specified in various ways. Three of these options require some input of physical parameters:

1. A homogeneous acousto-elastic half-space with **P-wave speed**, **S-wave speed**, **density**, **P-wave attenuation**, and **S-wave attenuation**;
2. A reflecting boundary with tabulated **reflection coefficients** (magnitude and phase) as a function of incident angle;
3. A Twersky scatterer[13] with a **bump density** and two **characteristic radii**

The bottom half-space may be specified in the same ways, except that it may not be described as a Twersky scatterer.

5.2 RAM

RAM is a parabolic equation propagation model.

5.2.1 Features

- Simple input specification
- Automatically calculates full-field (on requested range-depth grid) for single source depth
- Range-dependence / 3-D
- Range-dependence is handled by approximating medium as a sequence of range-independent regions. Accuracy is increased by increasing the number of regions.

5.2.2 Limitations

- Cannot calculate reverberation for active performance prediction
- Cannot specify multi-layered bottom
- Cannot specify surface properties or roughness of bottom
- Only does 2-D calculation (assumes gradual horizontal variations in environment)
- Code uses a single frequency; multiple values require multiple runs.

[13] Used primarily for under-ice propagation and probably not important here.

5.2.3 Model Inputs

The environment may be specified at any number of ranges, which do not have to be evenly spaced. Profiles are not interpolated in range but are assumed to change abruptly at the range boundaries specified.

At each range a profile is required which specifies the water column and bottom properties. The **water depth** must be specified; in addition, the **water sound speed**, **bottom sound speed**, **bottom density**, and **bottom attenuation** can be specified as a function of depth. The profiles do not have to be evenly sampled in depth. In the water column, the density is fixed at 1.00 gm/cm^3 and the attenuation is assumed to vanish.

Attenuation values can only be specified in dB/wavelength.

5.3 OASES

OASES is a wavenumber integration propagation model. OASES is an upgraded version of SAFARI, supporting more complex environments. The extension RDOAST is a range-dependent (2-D) version of OASES. The description below applies to RDOAST. The full OASES package includes several other extensions for more in-depth analysis. In particular, the OASS and OASSP modules allow estimation of reverberation through calculation of the backscattered field.

5.3.1 Features

- Multi-layered environment including any number of isovelocity fluids, fluids with sound speed gradients, isotropic elastic media, transversely isotropic layers, dispersive elastic layers, and poro-elastic layers
- Supports stratified fluid flow parallel to the direction of propagation
- Can model multiple source frequencies in a single run
- Range-dependence / 2-D
- Range-dependence is handled by approximating medium as a sequence of range-independent regions and marching the solution in range using a virtual source approach. Accuracy is increased by increasing the number of regions.

5.3.2 Limitations

- Computationally intensive when full capability is exploited.

5.3.3 Model Inputs

A multi-layered environment can be specified at each range step. Range steps may be irregularly spaced.

For each layer at each location, the **compressional wave speed**, **shear wave speed**, **compressional wave attenuation**, **shear wave attenuation**, and **density** can be specified. The interfacial roughness can be specified either through an RMS **interfacial roughness**, or a roughness **correlation length** and **spectral exponent**.

A **compressional wave speed gradient** in a fluid layer may be specified. Speed that changes continuously with depth must be specified using multiple layers; however, there is no limit to the number of layers that may be specified.

For a moving fluid, the **fluid flow speed** may also be specified.

A porous sediment layer is specified by thirteen parameters that are used in the Biot model.

A dispersive elastic layer is specified using a table of frequency-dependent compressional and shear speeds and attenuations.

5.4 BELLHOP

BELLHOP is a ray-theoretic propagation model. The theory is described in Porter and Bucker (1987)[14]. The version of BELLHOP maintained by the Ocean Acoustics Library (OALIB) is intended as a research model. A second version, designated BELLHOP-DRDC, is a trimmed-down version, intended to provide a simpler interface for the operational users at DRDC. A user's guide resides with Dr. William Roger, DRDC.

The following features and limitations apply to the DRDC version.

5.4.1 Features

- Fully range-dependent in bathymetry, sound speed and bottom loss province. It includes wind-driven surface loss, MGS bottom loss and Thorpe absorption.
- Employs a robust variant of Gaussian beam tracing, (GRAB style) with linear sound speed interpolation. For propagation loss, the number of rays and start/stop angles are set internally.
- Output choices are a ray trace, coherent or incoherent propagation loss matricies, or SALT tables (Sound angle, level and time) as a function of receiver depth and range. Propagation loss matricies provide data for full field color contour plots or single depth loss vs range style plots.
- Active reverberation can be constructed using the SALT table output.

5.4.2 Limitations

- Applicable only for 2D solutions.
- Code uses a single frequency and source depth. Multiple values require multiple runs.

[14] Porter, M.B. and H.P. Bucker, "Gaussian beam tracing for computing ocean acoustic fields." J. Acoust. Soc. Am. 82, 1349–1359 (1987).

- Sediment layering is not modeled. The solution is inaccurate if used in bottom-limited propagation conditions where bottom interactions can not be adequately described by a plane-wave Rayleigh reflection coefficient. (This is generally described by a low-frequency limit but it will also depend upon water depth).

5.4.3 Model Inputs

The model supports up to 10 arbitrarily spaced range dependent water column specifications. The input may specify either **sound speed** or **temperature** as a function of depth, for a maximum of 100 depths. Leroy's equation (1969) is used to convert temperature to sound speed, assuming open ocean conditions and 35 ppt salinity. Sound speed is linearly interpolated during ray tracing.

Similarly, the model supports up to 10 arbitrarily spaced range dependent bottom specifications, via a **MGS bottom loss province** at each range. Finally, the model supports up to 100 arbitrarily spaced range dependent bathymetry specifications.

6. Summation

In sections 3 through 5 GD Canada has summarized and highlighted published work that might be of further interest to the Scientific Authority, and which addresses the research topics outlined in section 1.3. Section 6.1 attempts to summarize the central themes that can be extracted from the work that has been reviewed. Section 6.2 presents recommendations for the way forward into phase II of the project.

6.1 Results

One theme that emerges from the literature review is that there have been a fairly large number of ocean experiments where a detailed characterization of the shallow-water environment has been paired with repeated acoustic measurements. The environmental characterizations are very useful for determining typical values and variabilities for environmental parameters of interest. Many of the papers based on these experiments include model-data comparisons, which may serve as a useful basis for our work in phase III.

We also note that there are several papers that derive analytical or quasi-analytical expressions for the sensitivity of the acoustic field to environmental perturbations. These may serve as a useful basis for comparison or contrast to our work in phase II.

The bulk of the work summarized here concerns uncertainty and variability in the environment. On the one hand, some researchers are working to *characterize the uncertainty in the prediction* more accurately, so that it can be effectively communicated to the user. On the other hand, others are working to *reduce the prediction uncertainty*. Later phases of this study can potentially make a contribution to both of these efforts, but is more relevant to the second objective, if it can help identify which input uncertainties are most important and therefore need to be reduced.

From all the papers reported and reviewed, along with the Uncertainty DRI final reports, it appears that much work remains to be done at the system level before sonar performance prediction models can achieve practical improvements in shallow water areas. The PROSIM team and the UNITES team of the Uncertainty DRI are both studying the system-level impact of environmental variability, albeit in different ways.

Within the groups studing seabed variability there appear to be two approaches or views as to which environmental parameters are most important. One group sees importance in the sediment properties, grain size, layer types and depths, while the other group is more concerned with higher resolution bathymetry, bottom contours, and maps of the bottom topography. It should be a goal of this study to contribute to the resolution of this debate.

6.2 Recommendations

Phase II asks for an overview of the sensitivity of acoustic propagation on measurable quantities, working from general physical principles and from specific acoustic models.

Meeting the objective for this phase requires developing a sensitivity measure that is meaningful for acoustic propagation, together with a systematic plan to study acoustic sensitivity to the environment. Linear and non-linear sensitivity measures are described in Annex A.

In our response to the RFP, we proposed that the nonlinear sensitivity measure and Monte Carlo sampling outlined in Annex A provide an approach to examine sensitivity and the effects of nonlinearity in acoustic sensitivity. As noted in that description, it will be necessary to identify a small number of oceanographic and geoacoustic parameters to include in the analysis. This choice may depend on the specific environments and acoustic scenarios that are chosen for study.

Before proceeding with phase II, then, the team and the scientific authority must agree on:

- The frequencies of greatest interest;
- The acoustic observables of greatest interest (e.g. transmission loss, reverberation);
- The environments of greatest interest, recalling that the proposal suggests starting with a range-independent environment before proceeding to a range-dependent environment;
- The parameters most likely to be important in these scenarios and environments, based on the literature review presented here;
- Typical mean values and variability in those parameters, based on the literature review so far; and
- The propagation models most suitable for the sensitivity analysis, based on the scenarios, environments, and parameters to be studied.

Based on the literature review presented here, we could make a tentative conclusion that the water column sound speed profile has the most significant effect on acoustic propagation; the temporal and spatial variability associated with internal waves seems to be especially relevant in shallow water. On the other hand, it appears that this subject has had more scrutiny than the influence of the bottom properties, and therefore might not be the first priority of this study. Of the bottom-related properties, we would suggest including the bathymetry, compressional sound speed (and possibly its gradient), and sediment layer depth in the sensitivity analysis.

Concerning the choice of models, we would suggest that a comparison using more than one model would be advantageous, since there can be significant differences between models even for the same nominal environment.

7. List of Acronyms

APL-UW	Applied Physics Laboratory at the University of Washington
ARL/PSU	Acoustics Research Laboratory at the Pennsylvania State University
ASCOT	Assessment of Skill for Coastal Ocean Transients
ASIAEX	Asian Seas International Acoustics Experiment
BLUG	Bottom Loss Upgrade
DND	Department of National Defence
DRI	Directed Research Initiative
ECS	East China Sea
GDB	Geophysical Database
IEEE	Institute of Electrical and Electronics Engineers
MBES	Multibeam echo sounder
MGS	Marine Geophysical Survey
NATO	North Atlantic Treaty Organization
NAVOCEANO	Naval Oceanographic Office (USA)
NMFS	National Marine Fisheries Service (NOAA)
NOAA	National Oceanic and Atmospheric Administration (USA)
NRL	Naval Research Laboratory
OASIS	Ocean Acoustical Services and Instrumentation Systems
ONR	Office of Naval Research (USA)
PE	Parabolic Equation

RAM	Range-dependent Acoustic Model
SACLANT	Supreme Allied Commander Atlantic (NATO)
SACLANTCEN	SACLANT Undersea Research Centre
SAFARI	Seismo-Acoustic Fast field Algorithm for Range-Independent Environments
SCS	South China Sea
SIO-UCSD	Scripps Institution of Oceanography, University of California San Diego
SWARM	Shallow Water Acoustic Propagation in Random Media
TL	Transmission Loss
UNITES	Uncertainties and Interdisciplinary Transfers Through the End-to-End System
VBES	Variable beam echo sounder
WHOI	Woods Hole Oceanographic Institute

Annexes

Annex A – Sensitivity Measures

The following segment has been extracted from GD Canada's response to the Geoacoustic Sensitivity Study RFP. This is section 2.2.1.3 of that document.

The objectives of the proposed work require developing a representative measure of parameter sensitivity that is meaningful for acoustic propagation, together with efficient and effective computation procedures.

For the purposes of this work, sensitivity is taken to mean an appropriate measure of the effect on acoustic measurements of realistic variations in ocean environmental parameters (due to errors/uncertainties in parameter values, spatial and/or temporal variability, etc.). Since use of a number of different propagation models will likely be required to cover the scope of this project, the goal here is to develop an approach that is applicable to any propagation model.

It is important to note at the outset that estimating acoustic sensitivity is a forward problem, and differs from inverse problems such as geoacoustic inversion and source localization. To define notation, let **m** represent the vector (model) of environmental parameters and **d** be the vector of acoustic responses (data) corresponding to propagation in the environment described by **m**. The physics and numerics of the acoustic forward problem (modeling propagation for a known environment) have been studied extensively, and a variety of suitable numerical solutions exist. Forward modeling simulates a natural process (acoustic propagation), and hence has the desirable properties of existence, uniqueness, and stability (i.e., a small change in **m** produces only a small change in **d**). Conversely, a solution to the inverse problem of estimating environmental parameters from measured data may or may not exist, is generally non-unique, and often unstable. Further, for non-linear problems, there is no general algorithmic formulation for the inversion process and search or sampling methods are typically employed[15,16,17].

The concept of sensitivity is well-defined for linear problems, which provide a basis for addressing non-linear acoustic problems. A linear problem can be represented in matrix form as

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[15] S. E. Dosso, M. J. Wilmut and A. L. Lapinski, "An adaptive hybrid algorithm for geoacoustic inversion," *IEEE J. Oceanic Eng.*, **26**, 234–326 (2001).

[16] S. E. Dosso, "Quantifying uncertainties in geoacoustic inversion, I: A fast Gibbs sampler approach," *J. Acoust. Soc. Am.*, **111**, 129–142 (2002).

[17] S. E. Dosso and P. L. Nielsen, "Quantifying uncertainties in geoacoustic inversion, II: Application to a broadband shallow-water experiment," *J. Acoust. Soc. Am.*, **111**, 143–159 (2002).

$$\mathbf{d} = \mathbf{A}\mathbf{m}. \quad (1)$$

A is commonly known as the sensitivity matrix[18], and has elements

$$A_{ij} = \frac{\partial d_i}{\partial m_j}, \quad i = 1, N, \quad j = 1, M, \quad (2)$$

The partial derivatives in Eq. (2) quantify the rate of change of the data with respect to the model parameters and can themselves be used as a relative measure of sensitivity. However, sensitivity based on partial derivatives does not take into account the potentially wide variation of uncertainties associated with different environmental parameters (e.g., the uncertainty of water-column sound speed may be of the order of a few meters/second, while the seabed sound speed may be uncertain over 100s of meters/second). Hence, it is useful to consider the variability in the data due to specific changes in the model parameters. The change in the *i*th datum due to a change δm_j to the *j*th parameter of a background model **m** is given by

$$\delta d_i^j = d_i(m_j + \delta m_j) - d_i(m_j), \quad (3)$$

where the explicit dependence on the parameters that are unchanged is suppressed for simplicity. By linearity, this difference can also be expressed

$$\delta d_i^j = \frac{\partial d_i}{\partial m_j} \delta m_j. \quad (4)$$

The advantage to Eq. (4) is that, given the required partial derivatives, changes to the data can be computed for any parameter change without applying the full forward model.

Sensitivity cannot be quantified meaningfully without some consideration of the underlying uncertainty distributions that it represents, since only for simple distributions can sensitivity be interpreted in a straightforward manner. Equation (4) indicates how uncertainties propagate from model parameters to the computed data for a linear problem: if the uncertainty for parameter m_j is Gaussian distributed with standard deviation σ_j, then the corresponding uncertainty for the *i*th datum is also Gaussian with standard deviation given by $|\partial d_i/\partial m_j|\sigma_j$ (i.e., the derivative acts as a magnification factor). A measure of the sensitivity of datum d_i to parameter m_j that is independent of data/parameter scales and units is given by

[18] W. Menke, *Geophysical Data Analysis: Discrete Inverse Theory* (Academic Press, New York, 1984).

$$s_{ij} = \frac{|\delta d_i^j|}{|d_i|}. \tag{5}$$

The sensitivity defined in Eq. (5) depends on the size of the particular model perturbation δm_j, indicating that a comparison of the relative importance of various environmental parameters depends on the uncertainties associated with those parameters. A physically meaningful choice is to consider parameter perturbations that are equal to their assumed standard deviations, i.e.,

$$s_{ij} = \frac{|\delta d_i^j(\delta m_j = \sigma_j)|}{|d_i|}. \tag{6}$$

Equation (6) defines a linear sensitivity measure. For a linear problem with Gaussian-distributed parameter uncertainties, s_{ij} given by Eq. (6), represents the ratio of the standard deviation for the *i*th datum (due to the uncertainty in the *j*th parameter) to its expected value. In this case, s_{ij} is equivalent to the coefficient of variation, a standard statistical measure used for comparing the variability of potentially disparate quantities[19]. If the model-parameter uncertainties (standard deviations) are not well known, representative values can be employed as linearity allows for a simple understanding of how the sensitivity scales with the parameter uncertainty (e.g., if σ_j is doubled, s_{ij} doubles).

The above concepts can be extended to non-linear problems such as acoustic propagation, although care must be taken to ensure that the results remain meaningful. Expanding the non-linear data functional for a perturbed model (*j*th parameter) about the background (unperturbed) model yields

$$d_i(m_j + \delta m_j) = d_i(m_j) + \frac{\partial d_i(m_j)}{\partial m_j}\delta m_j + O\left|\delta m_j\right|^2. \tag{7}$$

Neglecting higher-order terms leads to an approximate local linear relationship between data and model perturbations

$$\delta d_i^j \approx \frac{\partial d_i(m_j)}{\partial m_j}\delta m_j. \tag{8}$$

(cf. Eq. (4) for linear problems). It is possible to use this expression in the linear sensitivity measure given in Eq. (6). Analytic approaches to computing partial

[19] R. E. Walpole, *Introduction to Statistics, Third Edition* (Macmillan Pub., New York, 1982).

derivatives have been derived for normal-mode propagation models[20,21]; for other propagation models derivatives can be estimated numerically. However, Eq. (8) is only a local approximation because higher-order terms are neglected and because, unlike the linear case, the partial derivative depends on the background model at which it is evaluated and its value can vary significantly away from this model. Hence, it is preferable to calculate δd_i^j in Eq. (6) as the difference of modeled data according to Eq. (3), applying the non-linear propagation model. This procedure is exact (i.e., makes no linear approximation) and is applicable for any propagation model, at minor computational cost.

Even using the exact expression for δd_i^j, care must be taken in interpreting linearized sensitivities, since for non-linear problems Gaussian-distributed model uncertainties do not imply Gaussian data uncertainties. Strong nonlinearity can lead to complicated, potentially multi-modal data uncertainty distributions, which preclude a simple linear interpretation of sensitivity. To address nonlinearity, the full data uncertainty distribution can be estimated using Monte Carlo sampling[22]. This procedure is based on drawing random model perturbations δm_j from a Gaussian distribution with zero mean and standard deviation σ_j, and computing the corresponding data perturbation δd_i^j for each sample according to Eq. (3). Sampling continues until the distribution converges in data space (convergence can be monitored by inter-comparing several independent distributions collected in parallel). A non-linear sensitivity measure, analogous to the linear measure in Eq. (6), is based on the standard deviation of the data perturbations

$$s_{ij} = \frac{\left\{ < \left[\delta d_i^j - < \delta d_i^j > \right]^2 > \right\}^{1/2}}{|\, d_i \,|}, \tag{9}$$

where the expected value <·> represents an ensemble average over the Monte Carlo samples. Note that since the Monte Carlo forward-modeling is carried out for only one parameter m_j at a time, the non-linear sampling approach is not computationally intensive, and should converge in orders of magnitude fewer forward computations than sampling approaches applied to multi-dimensional acoustic inverse problems[16,17]. Hence, we recommend using Eq. (9) initially to calculate non-linear sensitivities for a particular scenario. If the data uncertainty distributions obtained in this manner are well-behaved and sensitivities based on Eqs. (6) and (9) are similar, the simpler linear measure of Eq. (6) is justified and can be used subsequently. For non-linear problems it does not follow automatically that the sensitivity s_{ij} scales with parameter

[20] P. Gerstoft, "Inversion of acoustic data using a combination of genetic algorithms and Gauss-Newton approach," *J. Acoust. Soc. Am.*, **97**, 2181–2190 (1995).
[21] R. T. Kessel, "The variation of modal wave numbers with geoacoustic parameters in layered media," *J. Acoust. Soc. Am.*, **102**, 2690–2696 (1997).
[22] W. H. Press et al., *Numerical Recipes, Second Edition* (Cambridge University Press, Cambridge, 1986).

uncertainty σ_j in a simple way; this can be investigated by applying Eq. (9) for a range of values of σ_j.

Given that Eqs. (6) and/or (9) provide meaningful sensitivities for a particular datum d_i, the issue remains that these measures are generally too specific for the purpose of determining the relative importance of environmental parameters. Propagating acoustic fields represent complicated interference patterns that are highly variable functions of source-receiver geometry, and hence the sensitivity for a particular datum may not be representative of the overall sensitivity of the field. To address this, data sensitivities can be spatially averaged to obtain a stable, representative sensitivity measure. In general, averaging over source and receiver depths relevant to the particular acoustic application is of primary importance. Kessel[23] developed an analytic procedure for approximating a depth-averaged sensitivity measure (similar to the linear measure defined above) for adiabatic-mode propagation, without carrying out any actual averaging. However, as most propagation models provide acoustic responses at multiple depths in a single run, explicit averaging can be applied using the results of only a small number of runs (e.g., 5–10) with different source depths. Explicit averaging provides a general approach to sensitivity stabilization that is applicable for any propagation model at a modest computational cost. To be specific, if the data index $i=1,N$ is taken to represent various combinations of N_s source depths and N_r receiver depths (with $N = N_s N_r$), the depth-averaged sensitivity can be defined

$$s_j = \frac{1}{N}\sum_{i=1}^{N} s_{ij}, \qquad (10)$$

with s_{ij} computed according to Eq. (6) or (9), as appropriate. Depth-averaged sensitivities s_j can be computed for a sequence of source-receiver ranges to examine the range dependence of the sensitivity; frequency dependence can be considered in a similar manner.

Finally, parameter sensitivities depend on the background model **m** about which variations are considered. This dependence can be addressed by evaluating the sensitivity separately for several different scenarios that are representative of the diversity of environments of interest as defined in consultation with the Scientific Authority.

[23] R. T. Kessel, "A mode-based measure of field sensitivity to geoacoustic parameters in weakly range-dependent environments," *J. Acoust. Soc. Am.*, **105**, 122–129 (1999).

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