Comparing Acoustic Uncertainty Predictions in Shallow Ocean Environments

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LONG-TERM GOALS

In recent decades, sophisticated computational routines for underwater acoustics have been developed, and advances in computational power have put real time use of these routines in reach for sonar applications. However, the US Navy must often operate in unfamiliar waters where the basic environmental inputs to the computational routines may be uncertain or unknown. In this situation, the value of computations must be assessed because uncertainty in environmental parameters translates directly into uncertainty in acoustic field predictions.

The long term goals of this project are: *i*) to quantitatively determine the uncertainties in underwater sound field predictions that arise from uncertainty in environmental parameters, *ii*) to compare the performance of different schemes for determining acoustic uncertainty, and *iii*) to determine how to exploit in-situ acoustic measurements and the generic propagation characteristics of underwater sound channels in order to enhance the performance of active and passive sonar systems in unknown or uncertain ocean environments.

OBJECTIVES

This project seeks to quantitatively determine what can be predicted with underwater sound calculations for uncertain ocean environments. The capabilities of future Navy sonar systems will be enhanced if they can fully exploit modern calculation techniques for underwater sound propagation. Unfortunately, imperfect knowledge of an ocean environment causes sound propagation calculations to be inherently uncertain. However, the accuracy limits of sound propagation calculations with uncertain input parameters and boundary conditions are not readily determined from the calculation routines themselves. Thus, the present objectives of this project are: *a*) to quantitatively predict the uncertainty in the acoustic amplitude predicted by ocean acoustic propagation simulations that comes from uncertainty in the parameters and boundary conditions (water column depth and sound speed, bottom slope, bottom density and sound speed, etc.) used to specify the computational environment for the acoustic propagation calculations, and *b*) to quantitatively compare the performance of acoustic uncertainty predictions from: the field shifting approach developed as part of this research effort, the polynomial chaos techniques being developed at NRL, and direct-simulation and/or Monte-Carlo methods.

APPROACH

This project primarily exploits analytical and computational propagation models for narrowband sounds in shallow ocean environments. In particular, an existing modal sum propagation model

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14. ABSTRACT
In recent decades, sophisticated computational routines for underwater acoustics have been developed, and advances in computational power have put real time use of these routines in reach for sonar applications. However, the US Navy must often operate in unfamiliar waters where the basic environmental inputs to the computational routines may be uncertain or unknown. In this situation, the value of computations must be assessed because uncertainty in environmental parameters translates directly into uncertainty in acoustic field predictions.

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(KRAKEN) is used for sound field calculations from 100 Hz to 1 kHz at ranges from 1 km to 10 km in sound channels having depths of 50 m to 200 m with depth-dependent sound speed. These propagation calculations have been used to develop an approximate technique for efficiently determining the probability density function (PDF) of acoustic amplitude, A, when one or more environmental parameters are uncertain and the PDFs of these uncertain parameters are known. In addition, a new recursive polynomial chaos (PC) solution has been developed for the Pekeris waveguide within the narrow-angle parabolic approximation of the wave equation. This recursive solution is an extension of the narrow-angle parabolic-equation ideal-waveguide PC solution [1]. The work described in this report is a portion of the doctoral research of Mr. Kevin R. James, who should complete his graduate studies in December 2008.

WORK COMPLETED

During the past year, this project has sought to determine how PDF(A) depends on range r and depth z for a harmonic sound field in an uncertain range independent sound channel described by N uncertain parameters. Although intellectually intriguing, PDF transport theory [2] was not pursued because there is, as yet, no way to calculate the requisite higher-order conditional moments. Instead, the field-shifting (FS) technique [3] was further developed and tested. This technique is based on the fact that changes in environmental parameters often lead to spatial shifts in computed acoustic fields [4]. For the FS technique, PDF(A) is constructed from N + 1 acoustic field calculations: one reference calculation, A_o, and N appropriately-shifted sensitivity-assessment calculations A_i. From these, an approximate multi-dimensional sensitivity curve is obtained:

$$A(r,z,\psi_1,\psi_2,...,\psi_N) \approx A_0 + \sum_{i=1}^{N}\left(\frac{\psi_i - \langle\psi_i\rangle}{\overline{\psi}_i - \langle\psi_i\rangle}\right)\left[A_i - A_0\right] \tag{1}$$

where ψ_i is the i^{th} uncertain parameter, the $\langle\ \rangle$-brackets denote an expected value, and $\overline{\psi}_i = \langle\psi_i\rangle + \Delta_i$ where Δ_i is a representative measure of the width of the input distribution of ψ_i. For the results reported here, Δ_i was set equal to one standard deviation, σ_i. Production of PDF(A) then proceeds directly from (1) using uniform or Monte-Carlo sampling techniques. The advantage of using (1) is that the number of field calculations, N + 1, is logarithmically less than the number, $\sim 10^N$, of samples necessary to create an accurate PDF(A), Such computational savings may allow the FS technique to be used in real time.

A sample result from the FS technique is provided for the range independent sound channel shown in Fig. 1. This sound channel is characterized by eight parameters and all eight are uncertain in this example. Figure 2 shows PDF(A) for a 400 Hz acoustic field when the sound channel is 50 m deep and the field point is at a range and depth of 6 km and 25 m, respectively. The three curves on Fig. 2 come from: numerically-converged direct Monte-Carlo sampling based on one million field calculations (solid), the field shifting technique based on nine field calculations (dashed), and simple multidimensional linear fitting using the same nine field calculations as the FS technique (dotted). Here the uncertain input parameters were Gaussian distributed with relatively small uncertainties; $\sigma_i/\langle\psi_i\rangle$ was typically just a fraction of a percent. However, the σ_i were chosen so that all eight parameters make approximately equal contributions to the final PDF shape. In this case, the FS PDF is closer to the numerically converged PDF than the linear-fitting PDF. The overall finding is that the FS technique is superior to simple linear fitting while having the same computational cost.

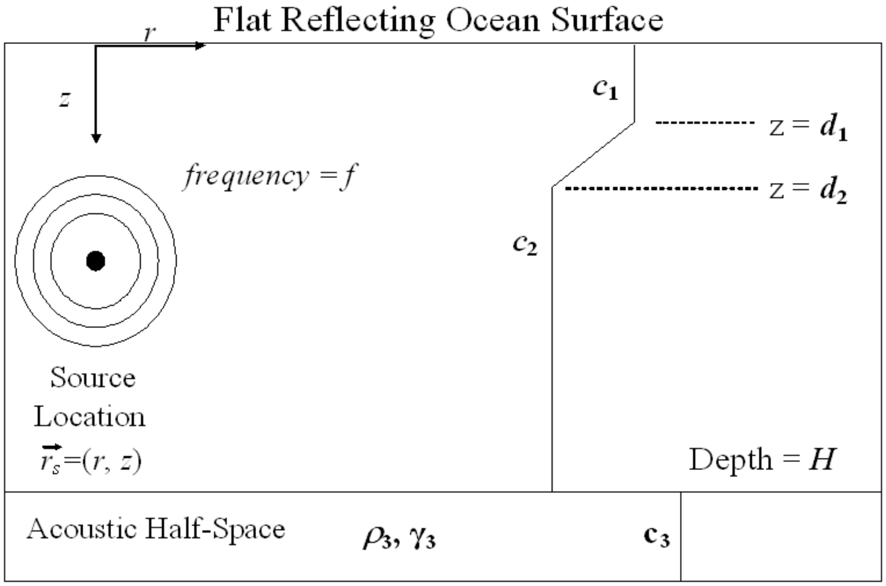

Figure 1. Schematic of a generic range-independent sound channel that is described by eight parameters: overall depth H, mixed layer depth d_1, thermocline lower limit d_2, mixed layer sound speed c_1, deep water-column sound speed c_2, bottom sound speed c_3, bottom density ρ_3, and bottom absorption coefficient γ_3.

The next step in this investigation has been to compare the FS technique for acoustic uncertainty prediction with results from the statistically sophisticated polynomial chaos (PC) approach that is currently under development at NRL under the direction of Dr. Steve Finette. The underwater sound PC literature includes only one worked example that is relevant for comparisons with the FS technique; a range-independent sound channel having perfectly-reflecting surface and bottom with uniform but uncertain speed of sound [1]. Unfortunately, at any range-depth location in this ideal waveguide, the amplitude of the acoustic field is independent of the speed of sound (sound speed uncertainty translates into phase uncertainty alone). This limitation makes such an environment unsuitable for field amplitude-uncertainty comparisons involving the PC and FS techniques. However, the existing ideal-waveguide PC solution technique can be extended to a Pekeris waveguide with an uncertain water column sound speed. This PC solution extension was recently completed as part of this project, with the expected finding that, in a Pekeris waveguide environment, sound speed uncertainty produces uncertainty in both acoustic-field amplitude and phase. Thus, genuine comparisons of PC and FS techniques are now possible in a Pekeris waveguide.

RESULTS

Preliminary comparisons of the FS and PC techniques at 150 Hz are provided on the next two figures. In both cases the waveguide is 200 m deep, the average water column sound speed is 1500 m/s, the bottom sound speed and density are 1650 m/s and 1900 kg/m^3, and the source and field-point locations are 40 meters deep. Figure 3 shows the sensitivity of acoustic amplitude to variations in the water column sound speed at a range of 3 km. The three curves are: the results from direct simulations (DS) involving field calculations at over 100 different sound speeds (solid), PC results using a recursively selected expansion order (dashes), and FS results from two field calculations (dots). Here, the DS sensitivity curve is the correct answer, and it is reassuring to see that both the PC and FS curves fall close to it. The range of the vertical axis of Fig. 3 has been chosen to magnify the differences between curves.

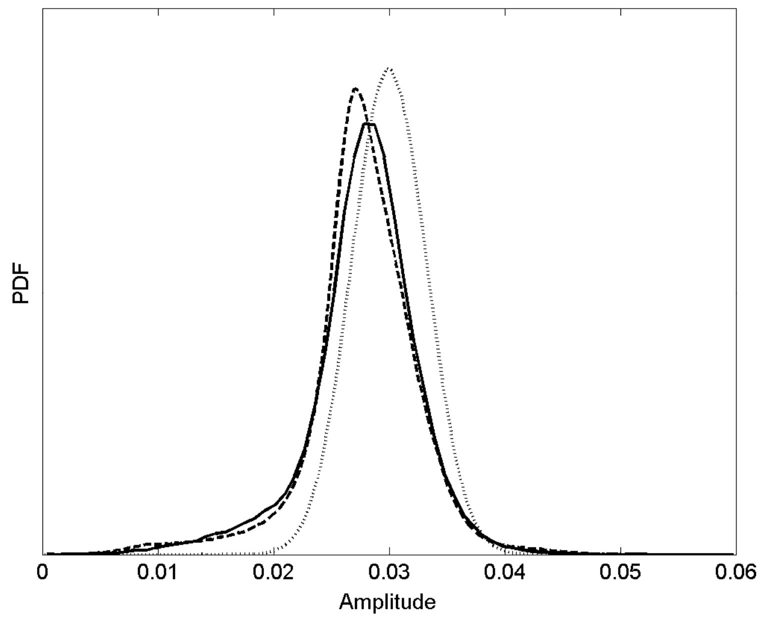

Figure 2. Comparison of acoustic amplitude PDFs from field-shifting (dashed line, nine field calculations), simple linear fitting (dotted line, nine field calculations), and numerically-converged direct Monte-Carlo sampling (solid line, one million field calculations) for f = 400 Hz at (r,z) = (6.0 km, 25 m) when all eight parameters of the Fig. 1 sound channel are uncertain.

The inaccuracies in estimates of PDF(A) that arise because of the errors in the PC and FS sensitivity curves are quantified in this investigation via a dimensionless absolute-value error norm:

$$L_1 = \int_o^\infty \left|\mathrm{PDF}_a(A) - \mathrm{PDF}_{DS}(A)\right| dA \ , \tag{2}$$

where $\mathrm{PDF}_a(A)$ is an approximate PDF from either the PC or FS technique, $\mathrm{PDF}_{DS}(A)$ is the numerically-converged direct-simulation PDF. This error norm has a well-defined range, $0 \le L_1 \le 2$, with $L_1 = 0$ and 2 implying a perfect match and mismatch, respectively. Typically, $L_1 < 0.2$ implies a good visual match between $\mathrm{PDF}_a(A)$ and $\mathrm{PDF}_{DS}(A)$ while L_1 near or above unity implies a poor match. For example, the L_1 values for FS and linear-fitting PDFs in Fig. 2 are 0.12 and 0.45, respectively.

A sample PDF-accuracy comparison as function of range in the Pekeris waveguide specified above is provided on Fig. 4. Here, the PC-derived PDFs consistently produce lower L_1's so the PC approach can be considered a more accurate technique for the chosen parameters for narrow-angle parabolic-equation-propagation in a Perkeris waveguide. However, there are two important caveats. First, these are preliminary results for a single uncertain variable in a highly-idealized sound channel. Comparisons involving different environmental and acoustic parameters, range dependencies, multiple uncertainties, and stochastic waveguide properties have not yet been made. And second, a robust convergence criterion for selecting the expansion order, Q, in the current Pekeris-waveguide PC solution has not yet been found. The results presented here are based on terminating the PC expansion when the magnitude of the largest expansion coefficient exceeds the highest order coefficient by three orders of magnitude. However, this criterion occasionally fails and it requires repeated PC calculations terminated at all orders up to the finally-selected value of Q. For Fig. 4, the final values of Q were as low as 20 and as high as 70.

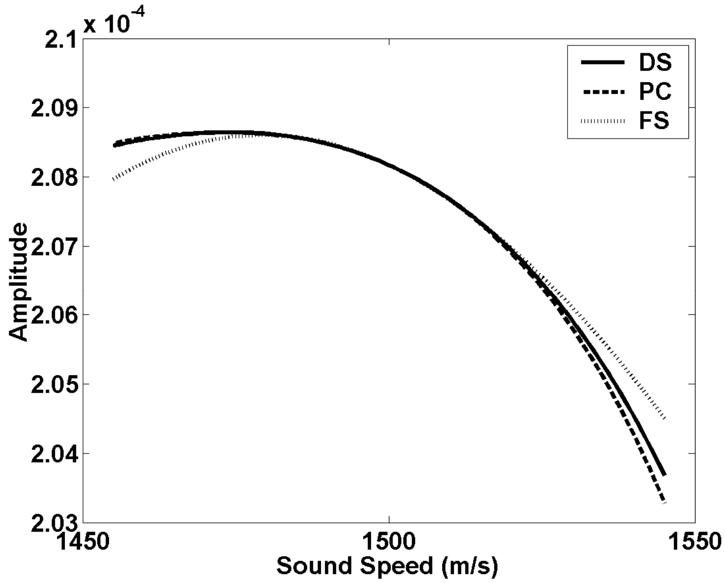

Figure 3. Acoustic amplitude variation as function of water-column sound speed in a Pekeris waveguide at 150 Hz. The waveguide is 200 m deep, the average water column sound speed is 1500 m/s, the bottom sound speed and density are 1650 m/s and 1900 kg/m^3, respectively. The source and field-point are 40 meters deep and separated by 3 km. The three curves correspond to: direct simulation (solid line) based on more than 100 field calculations at different water-column sound speeds, predictions from the polynomial chaos technique (dashed line), and predictions from the field shifting technique (dotted line) using two field calculations.

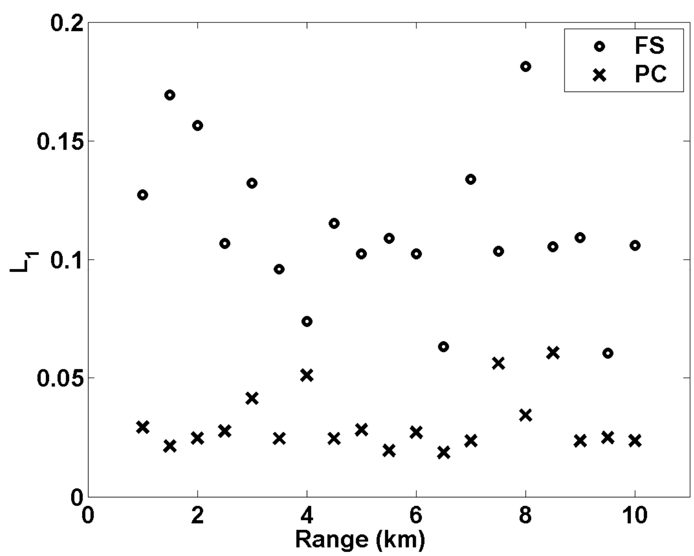

Figure 4. Absolute-value error norm, L_1, vs. the source-field point range in the Pekeris waveguide used to generate Fig. 3.

The current emphasis in this research project is to better understand the newly-derived PC solution, and expand the PC-FS comparison results and submit them for publication.

IMPACT/APPLICATION

In broad terms, this project ultimately seeks to determine what is possible for a sonar system when the available environmental and transducer-array information is less than perfect. The capabilities of future Naval sonar systems will be enhanced if acoustic propagation predictions and their uncertainty can be properly included in final results or in a tactical decision aid. Thus, this research effort on quantifying predicted-field uncertainties should eventually impact how transducer (array) measurements are processed for detection, localization, tracking, and identification. Moreover, this research may be pivotal in determining how the Navy obtains and uses acoustic uncertainty information.

TRANSITIONS

The results of this project should aid in the design of sonar signal processors for tactical decision aids, and in determining which features of an acoustic environment must be known accurately for effective sonar operations that involve use of acoustic field predictions. In particular, Dr. Lee Culver's ONR-funded REVEAL (Receiver Exploiting Variability in Estimated Acoustic Levels) sonar signal processing effort at Penn State ARL could benefit from the results of this investigation. In addition, the Navy's extensive large-scale ocean acoustic transmission-loss calculations as conducted by Drs. Josette Fabre (NRL Stennis) and Ruth Keenan (SAIC) might be simplified or reduced through the use of PC, FS, and/or related techniques.

RELATED PROJECTS

Dr. Steve Finette's polynomial chaos program at NRL-DC is the research project that is most closely related to the current one. ONR is also funding an on-going multi-investigator experimental effort on environmental and acoustic uncertainty that has a greater emphasis on oceanography than the current single-investigator research effort.

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