Approximating Acoustic Uncertainty 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, and *ii*) 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 determine how to utilize propagation modeling and in-situ acoustic measurements to develop accurate acoustic field predictions for ocean environments.

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 (KRAKEN) is used for sound field calculations from 100 Hz to 1 kHz at ranges from 1 km to 10 km in sound channels with depths of 50 m to 100 m. The current graduate student, Mr. Kevin R. James, has used such calculations to develop a new approximate technique for efficiently determining the

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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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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.

WORK COMPLETED

During the past year, this project has sought to determine how PDF(A) depends on the range r and depth z for a harmonic sound field in an uncertain range independent sound channel. Four uncertain environmental parameters have been considered to date: water column depth, bottom density, depth-averaged speed of sound, and speed-of-sound profile shape. At this point, two potentially viable theoretical approaches to this problem have been identified: *i*) solution of probability transport equations [1], and *ii*) approximate transformation of uncertain parameter PDFs into field-amplitude PDFs via optimum spatial shifting [2].

The optimum-shift-based approximate-PDF technique relies on finding a approximate transformation relationships between N uncertain sound channel parameters by performing only $N + 1$ sound field calculations; one for the baseline environmental parameters (typically the expected values, herein denoted by $\langle\ \rangle$-brackets), and N sensitivity-assessment calculations where each uncertain environmental parameter is incremented by one standard deviation (herein denoted by σ with a subscript indicating the uncertain parameter). For example, to approximately determine PDF(A) at any (r,z)-location in a sound channel with an uncertain depth, H, two field calculations are necessary: one at with channel depth $\langle H\rangle$, and one with channel depth $\langle H\rangle + \sigma_H$. For many types of parameter changes the local difference between two such acoustic amplitude fields can be approximated by a range-depth spatial shift. Here the optimum spatial shifts leading to the minimum mean-square-difference between the baseline and sensitivity-assessment calculations are denoted by Δr_o and Δz_o. Once these optimum range and depth shifts have been found, an approximate depth-to-amplitude transformation relationship can be constructed for an arbitrary depth H:

$$A(r,z,H) \approx A\left(r\left(H/\langle H\rangle\right)^{\alpha}, z\left(H/\langle H\rangle\right)^{\beta}, \langle H\rangle\right), \tag{1}$$

where the exponents are determined from the optimum shifts:

$$\alpha = \ln\left(\frac{r+\Delta r_o}{r}\right) \Big/ \ln\left(\frac{\langle H\rangle + \sigma_H}{\langle H\rangle}\right), \quad \text{and} \quad \beta = \ln\left(\frac{z+\Delta z_o}{z}\right) \Big/ \ln\left(\frac{\langle H\rangle + \sigma_H}{\langle H\rangle}\right). \tag{2a, b}$$

Then, an approximate PDF for the acoustic amplitude, $\mathrm{PDF}_a(A)$, can be rapidly built from the known PDF (H) and (1) using standard techniques.

This technique is illustrated on Figures 1, 2, and 3. Figure 1 shows acoustic amplitude contours in a small range-depth field slice centered at a range of 3 km and a depth of 50 m at a frequency of 250 Hz in a range-independent sound channel with a silt bottom when the channel depth is $H = \langle H\rangle = 100$ m (a), and $H = \langle H\rangle + \sigma_H = 100.5$ m (b). Using these two calculations, the optimum shifts can be determined: $\Delta r_o = 27.5$ m and Δz_o. = 0.187 m. Placement of this information into (2) and then (1) allows an approximate amplitude vs. channel depth curve to be determined. Figure 2 shows this approximate curve (dashed line) along with a numerically-exact curve (solid line) and the results from a linear Taylor series approximation (finely-dotted line). The approximate and Taylor-series results are based on only two field calculations while the exact curve is based on 41. The results shown on Fig. 2 can be used to construct the acoustic-amplitude

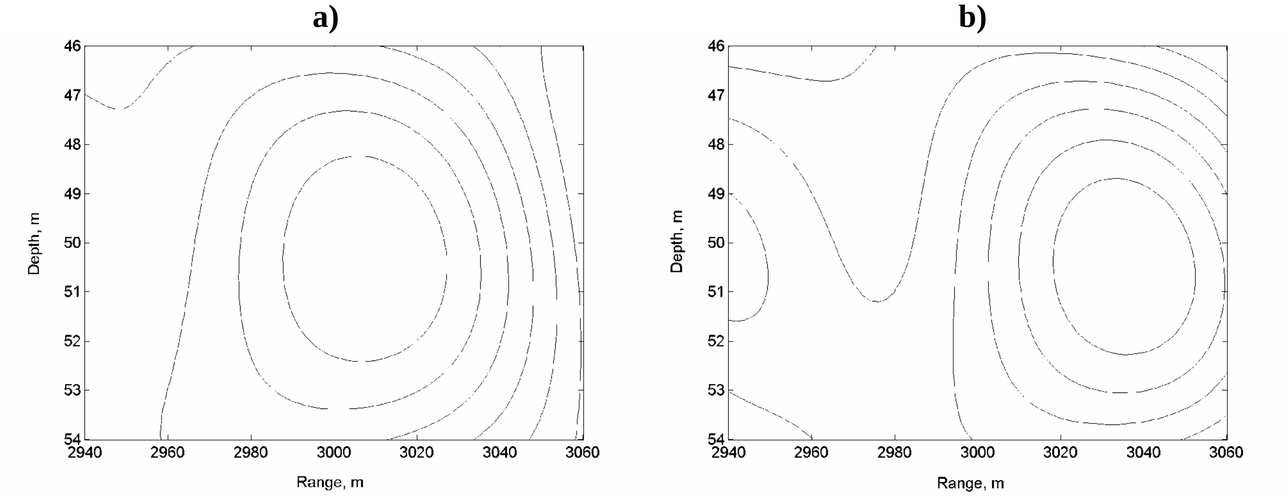

Figure 1. Contour plots of sound field amplitude in a small range-depth slice in a range-independent underwater sound channel when the channel depth is 100 m (a) and 100.5 m (b). The acoustic frequency is 250 Hz. Note that the primary difference is a range shift between the two fields.

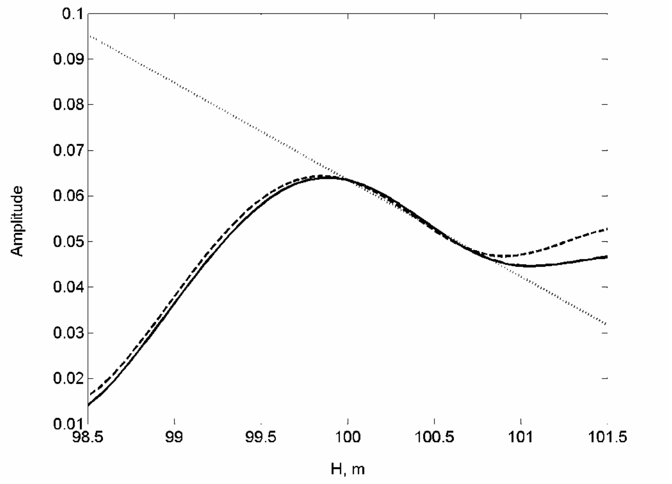

Figure 2. Acoustic amplitude at a range of 3000 m and a depth of 50 m vs. sound channel depth for fields shown in Fig. 1: exact relationship (solid line), approximate relationship based on (1) and (2) (dashed line), and approximate relationship based on a linear Taylor series (finely-dotted line). The exact curve is based on 41 field calculations while the two approximations are based on two. The shift-based curve matches the exact one well while the Taylor-series line does not.

PDFs shown on Fig. 3 for a sound channel having a Gaussian-distributed uncertainty in depth, H, with $\langle H \rangle$ = 100 m, and σ_H = 0.5 m. As in Fig. 2, the dashed curve is the approximate result, PDF$_a$(A), obtained from using (1) and (2), the solid curve is the numerically-exact result, PDF$_e$(A), and the finely-dashed curve is obtained from the linear Taylor series.

In this investigation, the quality of the match between the PDFs is quantified in terms of a dimensionless absolute-value error-norm:

$$L_1 = \int_o^\infty \left|\mathrm{PDF}_a(A) - \mathrm{PDF}_e(A)\right| dA \quad , \tag{3}$$

where $0 \le L_1 \le 2$, with $L_1 << 1$ implying a good match between the approximate and exact PDFs, L_1 near or above unity implying a poor match, and $L_1 = 2$ implying a complete mismatch.

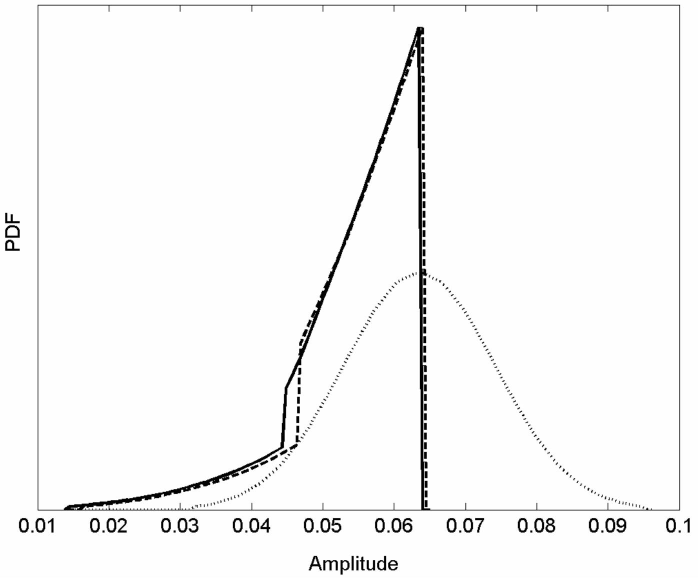

Figure 3. Acoustic amplitude PDFs determined from the curves shown in Fig. 2 when the sound channel depth is Gaussian-distributed with a mean of 100 m and a standard deviation of 0.5 m. Line types as in Fig. 2. The L_1 values for the approximate PDFs determined from optimum shifts and from a linear Taylor series are 0.1 and 1.0, respectively. So, as anticipated from Fig. 2, the shift-based PDF matches the exact one well while the Taylor-series result does not.

The optimum-shift-based approximate PDF construction technique has been found to be surprising robust but not perfect. In particular, it looses accuracy when the field variation between the baseline and the sensitivity assessment calculations does not correspond to a spatial shift. However, comparisons between the minimum root-mean-square (rms) difference of the calculated fields and the amplitude variance determined from PDF$_a$(A) can be used to indicate when the approximate technique will have less accuracy. Thus, PDF$_e$(A) does not have to be calculated to assess the likely accuracy of the PDF$_a$(A) results.

RESULTS

Test results for the optimum-shift-based approximate PDF construction technique are shown on Figure 4. Here L_1 values are plotted vs. the number of propagating modes in the sound channel when the sound channel is range independent with an isospeed sound profile, but channel depth has an rms uncertainty of 0.5% with a mean of 50 m, the sound speed has an rms uncertainty of 0.5% with a mean of 1450 m/s, and the bottom density has an rms uncertainty of 5% with a mean of 1650 kg/m^3. Here all three uncertain environmental parameters are Gaussian distributed. In each case, the approximate results required only 4 field calculations while the exact results required more than 9000.

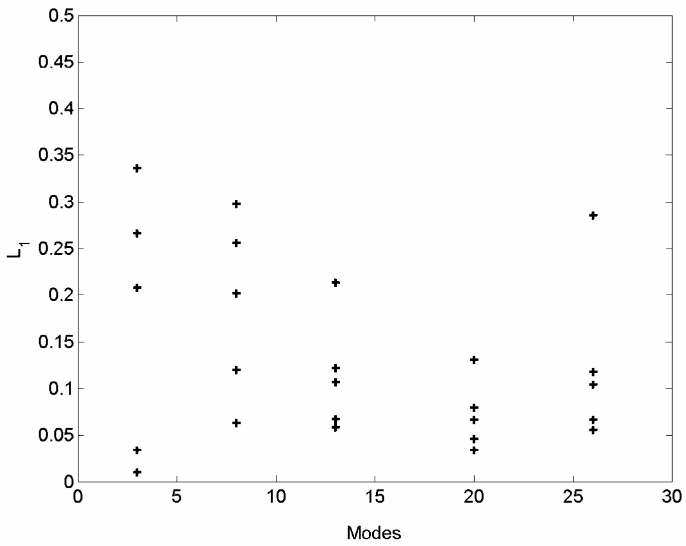

Figure 4. Absolute value error norm, L_1, vs. the number of propagating modes for in an iso-speed range independent sound channel having an uncertain depth (mean = 50 m with 0.5% rms), uncertain sound speed (mean = 1450 m/s with 0.5% rms), and uncertain bottom density (mean = 1650 kg/m^3 with 5.0% rms). Here all L_1 values are below 0.4 which indicates the shift-based approximate-PDF technique is successful.

Overall, this technique has been found to achieve L_1 values less than 0.5 in 95% of test cases. And, L_1 values less than 0.5 have been found to imply mean-amplitude and amplitude-variance estimates within 1.1 dB and 2.3 dB, respectively, of exact values for these moments. The current emphasis in this research project is to extend and confirm these results in more complicated sound channels, and to compare the performance of the optimum-shift-based approximate PDF technique with other uncertainty assessment and sensitivity assessment techniques.

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 should eventually provide a direct means for assessing acoustic uncertainties that is not available today.

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.

RELATED PROJECTS

Verbal agreements are in place with Dr. Steve Finette of NRL-DC and Dr. Lee Culver of the Penn-State ARL to coordinate and possibly collaborate on topics involving predicted-field uncertainties. Dr. Finette leads an NRL funded effort on acoustic uncertainty, and Dr. Culver is a co-investigator on an ONR-funded signal-processing project on the impact of uncertainty on sonar signal processing.

REFERENCES AND PUBLICATIONS

[1] James, K.R., and Dowling, D.R. 2005 “A probability density function method for acoustic field uncertainty analysis,” J. Acoust. Soc. Am. Vol. 118, 2802-2810.

[2] James, K.R., and Dowling, D.R. “A method for approximating acoustic field amplitude uncertainty,” submitted to the J. Acoust. Soc. Am., September 2007.

HONORS/AWARDS/PRIZES

Prof. David R. Dowling, the principal investigator on this project, has been selected by the Student Council of the Acoustical Society of America (ASA) to receive the 2007 ASA Student Mentor Award. The ASA Student Council presents this award every two years to recognize individuals who have served as exemplary mentors. The ASA’s Mentor Award is designed to honor exceptional ability in guiding the academic and/or professional growth of students and junior colleagues. The award will be presented at the upcoming ASA Meeting in New Orleans.