# Acoustics in Uncertain Ocean Environments

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## LONG-TERM GOALS

In the last two 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 will translate into uncertainty in the 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 accomplished with underwater sound in 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 environmental 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 ocean acoustic propagation calculations 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 and broadband sounds in guided-wave ocean acoustic environments. Existing propagation models are used for Monte-Carlo simulations to validate new theoretical approaches that are developed as part of this research effort. In particular, analytical propagation models are used for free-space (single path) and stratified two-fluid (two path) environments. Sound propagation in an ocean sound channel is

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simulated with the range-depth wide-angle parabolic-equation code RAM (by Dr. Michael Collins of NRL) and the mode-based propagation code KRAKEN (by Dr. Michael Porter of HLS Inc.). The current graduate student, Mr. Kevin James, is pursuing a theoretical effort to develop new ways to determine acoustic uncertainty via predictions of the probability density function (PDF) for the relevant acoustic field quantities.

**WORK COMPLETED**

During the past year, this project has sough to determine how the probability density function for acoustic amplitude depends on the depth and range 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*) transformation of parameter probability distributions into field probability distributions. Development of the second approach has been the primary focus of this project this past year.

The PDF transformation technique is based on finding an approximate transformation relationship between an uncertain sound channel parameter by performing two sound field calculations; one for the baseline environmental parameters, and a second one where the parameter of interest, denoted as $\eta$, has been perturbed by a small amount to $\eta + \Delta\eta$. For many types of parameter changes the local difference between two such acoustic amplitude fields is merely a spatial shift in range, $\Delta r$, and depth, $\Delta z$. This phenomenon is illustrated in the two panels of Figure 1. The first panel shows the calculated field amplitude in a range-depth patch in the middle of an underwater sound channel. The patch is extends 30 wavelengths in depth and 600 wavelengths in range. The second panel is the same range-depth patch when the sound channel depth is changed by 1%. The red and green boxes in each figure are at the same respective locations. By comparing the contents of the same-colored box pairs in Fig. 1 a) and b), it can be determined that the amplitude feature in the red box primarily shifts horizontally down range, while the amplitude feature in the green box shifts both vertically downward and horizontally down range.

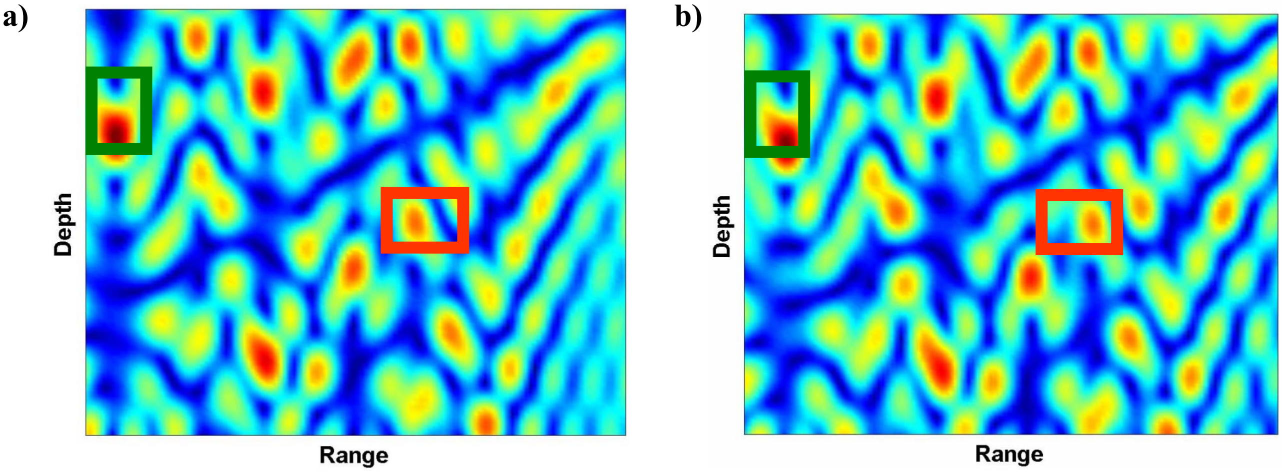


***Figure 1. Sound field amplitude on a range-depth slice in an underwater sound channel at the baseline sound channel depth (a), and when the sound channel depth is 1% larger than the baseline (b). Although the amplitude fields appear very similar, the features in the red box primarily shift down range while those in the green box shift downward and down range.***

A simple field-correlation procedure between the amplitude results in the two calculations allows two exponents ($\alpha,\gamma$) to be determined that characterize transformation from variations in $\eta$ to variations in range and depth:

$$\frac{r_o + \Delta r}{r_o} = \left(\frac{\eta + \Delta\eta}{\eta}\right)^{\alpha} \quad \text{and} \quad \frac{z_o + \Delta z}{z_o} = \left(\frac{\eta + \Delta\eta}{\eta}\right)^{\gamma}, \qquad (1,2)$$

where $r_o$ and $z_o$ are the range and depth of interest in the initial field. Although these equations are only valid locally, they allow variations in the uncertain environmental parameter to be transformed into changes in range and depth in the baseline sound field calculation. A sample result showing the success of this fitting and transforming procedure is provided in Figure 2 where predicted field amplitude at a single field point is displayed as a function of water column depth. The blue curve was obtained from approximately 100 field calculations, each having a slightly different depth. The red curve was obtained from the approximate approach described here and two field calculations at channel depths of 100.0 m and 100.1 m.

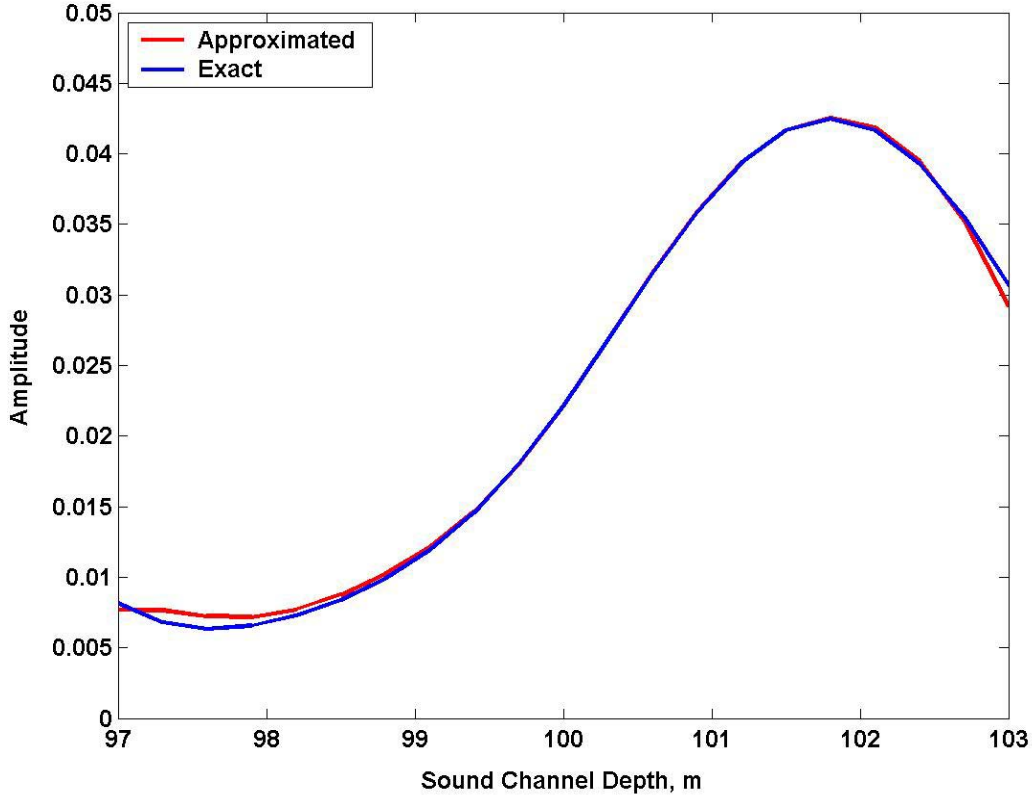


***Figure 2. Sound field amplitude (arbitrary units) at a point in an underwater sound channel as function of channel depth (in meters). The blue curve is a computationally exact result determined from many sound field calculations. The red curve is an approximate result using only two sound field calculations at channel depths of 100.0 m and 100.1 m.***

By appropriately weighting and summing samples of the acoustic amplitude along the curve specified by Eqs. (1) and (2) in the baseline prediction of the sound field, the PDF of $\eta$ can be converted into a PDF of acoustic amplitude. This procedure has been found to be accurate for changes in water column depth, bottom density, and depth-averaged speed of sound. This procedure has also been extended to handle multiple uncertain parameters (see below) as long as one additional field calculation is performed for each uncertain parameter. The computational advantage of this approach lies in the fact that only $N + 1$ calculations are necessary when there are $N$ uncertain parameters, while for direct Monte-Carlo simulations, the number of simulations necessary for $N$ uncertain parameters increases exponentially with $N$. The robustness of this technique is now under investigation.

Two disadvantages of this technique have been discovered to date. First, it does not perform well for an uncertain speed of sound profile because variations in the speed of sound profile cause distortions of the acoustic amplitude field that are not well described by range-depth spatial shifts. And second, the technique looses accuracy when the variations in the uncertain environmental parameters are large. For example, the technique works well in a range-independent shallow-ocean sound channel having a 1% root-mean-square (RMS) uncertainty in depth, but may be less suitable when this uncertainty is 10%. However, the importance of this second disadvantage is muted by the fact that when the environmental parameters have high uncertainty, predicted acoustic amplitudes typically also have high uncertainty, and, in such a highly uncertain realm, precise knowledge of the level of uncertainty may not be necessary. For example, the value of a sound field calculation for use with a tactical decision aid is likely to be low regardless of whether the amplitude has 12 dB or 15 dB of uncertainty.

**RESULTS**

Two sample results for the PDF of acoustic field amplitude in an uncertain sound channel are shown here. Both computationally exact results and approximate results are shown. The exact results were determined from many individual field calculations, while those obtained from the approximate techniques described here required only two or four field calculations.

Figure 3 shows the PDF of acoustic amplitude in a range independent sound channel having a single uncertain environmental parameter, the sound channel depth. The source-receiver range is 5 km. The sound speed profile is piece-wise linear and downward refracting near the ocean surface. The bottom density is 2000 $kg/m^3$ and its speed of sound is 1600 m/s. The acoustic frequency is 500 Hz. The source depth is 50 m, the receiver depth 20 m, and the nominal or mean sound channel depth is 100 m. The uncertainty in this depth is presumed to have a Gaussian distribution with a 1% (or 1 m) RMS deviation. The figure clearly shows that the computationally-exact and approximate results agree well. The means and standard deviations of the two field-amplitude distributions on Fig. 3 match to 3 significant figures.

Figure 4 shows the PDF of acoustic amplitude in a range independent sound channel having three uncertain environmental parameters: the sound channel depth, average water column sound speed, and bottom density. Here, the uncertainty in the average sound speed and bottom density are presumed to have Gaussian distributions with 1% and 8% RMS deviations, respectively. The geometry and the other parameters are the same as for Fig. 3.

Here again, the results are good even though the breadth of the amplitude distribution is more than 10 dB, but differences are apparent at the edges of the distributions. In this case, the means and standard deviations of the two field-amplitude distributions on Fig. 4 match to 2 significant figures.

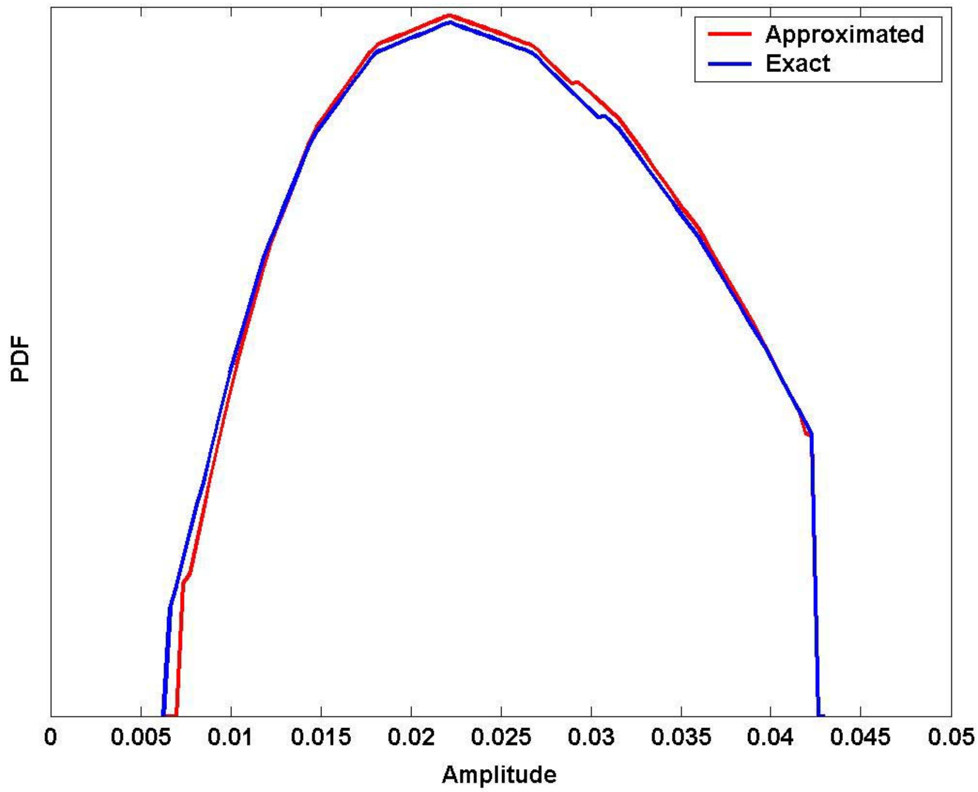


***Figure 3. Probability distribution of 500-Hz sound field amplitude at a 20 m receiver depth and a range of 5 km in a sound channel having a depth that is nominally 100 m with an RMS uncertainty of 1 m. The blue curve is a computationally exact result determined from 100 sound field calculations. The red curve is an approximate result determined from two sound field calculations.***

The current emphasis in this research project is extend and confirm these results, and then produce and submit of a journal article that describes the approximate technique and its performance.

## IMPACT/APPLICATION

In broad terms, this project 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 means for assessing acoustic uncertainties that is not available today.

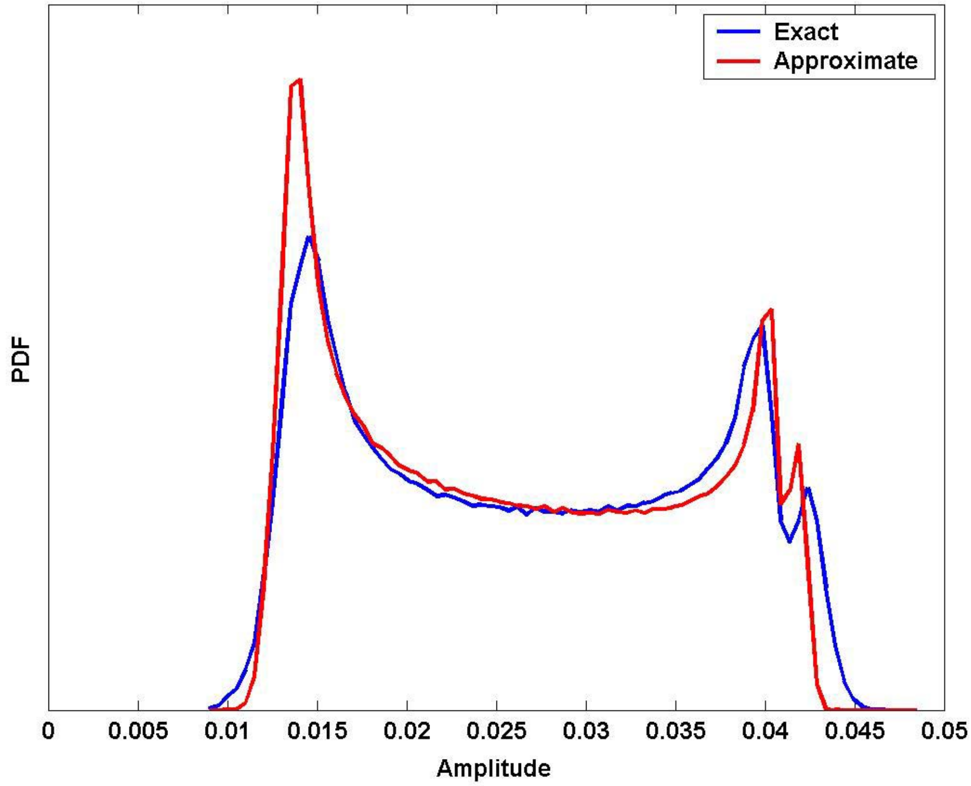


***Figure 4. Probability distribution of sound field amplitude at 500-Hz, mid water column, and a range of 4 km in a sound channel having uncertain depth, average sound speed, and bottom density. The blue curve is a computationally exact result determined from 8000 sound field calculations. The red curve is an approximate result determined from four sound field calculations.***

## 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

1. A verbal agreement is in place with Dr. George Smith of NRL-Stennis to coordinate and collaborate on future blind deconvolution efforts.

2. 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.

## HONORS/AWARDS/PRIZES

Mr. Kevin R. James, the Ph.D. student working on this project, won the student presentation contest in underwater acoustics at the 151$^{st}$ Meeting of the Acoustical Society of America in Providence, RI.