

# **Modeling and Analyzing the Propagation of Uncertainty from Environmental through Sonar Performance Prediction**

W.A. Kuperman, W.S. Hodgkiss, B.D. Cornuelle, A. Thode, and K.H. Kim

Scripps Institution of Oceanography

La Jolla, CA 92093-0238

phone: (858) 534-7990 / (858) 534-1798 / (858) 534-4021 / (858) 822-4864 / (858) 534-7048

fax: (858) 534-7641

email: [wak@mpl.ucsd.edu](mailto:wak@mpl.ucsd.edu) / [wsh@mpl.ucsd.edu](mailto:wsh@mpl.ucsd.edu) / [bdc@ucsd.edu](mailto:bdc@ucsd.edu) / [thode@mpl.ucsd.edu](mailto:thode@mpl.ucsd.edu) / [khkim@mpl.ucsd.edu](mailto:khkim@mpl.ucsd.edu)

Award Number: N00014 -01-1-0768

<http://www-mpl.ucsd.edu>

## **LONG-TERM GOALS**

Central to the long-term goals of this joint project is to understand the physics of the propagation of uncertainty through the interfaces between oceanography, acoustics, array processing and performance prediction. We will develop an efficient overall simulation platform that combines all of the components of the baseline (mean) and uncertainty problem: Oceanography through 4-D acoustic field prediction. The development of a methodology to distill the complexity and uncertainty of the ocean acoustic environment and the system level sensitivities to relevant situational awareness for the operator is an important goal of this research.

This project is a joint effort between the Principal Investigators listed above and the other team members: J. Krolik and L. Nolte (Duke University), H. Cox and K. Heaney (ORINCON), and M. Porter, P. Hursky, and M. Siderius (SAIC). Below we concentrate on the SIO effort.

## **OBJECTIVES**

The objective of this research program is both to develop a methodology to predict uncertainty in the whole performance prediction process and to understand the uncertainty physics of the individual components of the process. The latter provides the potential to develop methods to reduce uncertainty.

## **APPROACH**

We are following a two-pronged approach: (1) total model development for Monte Carlo simulation and (2) studying the physics of the interfaces between oceanography, acoustics, array processing and performance prediction.

One integral part of our approach to the total uncertainty simulation model development depends on the usual Monte Carlo runs to convert an ensemble of oceanographic states to an ensemble of system outputs showing the range of possible values. This method has the advantage of retaining validity in the presence of strong nonlinearity as well as being computationally simple. The ocean ensemble will be coupled to a wide area acoustic propagation model and an accurate array processing model for the purpose of performing area wide performance prediction with an uncertainty measure. Particular care will be given to the mode of representing this information to the operator.

## Report Documentation Page

*Form Approved*  
*OMB No. 0704-0188*

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1. REPORT DATE <b>30 SEP 2003</b>	2. REPORT TYPE	3. DATES COVERED <b>00-00-2003 to 00-00-2003</b>			
4. TITLE AND SUBTITLE <b>Modeling and Analyzing the Propagation of Uncertainty from Environmental through Sonar Performance Prediction</b>		5a. CONTRACT NUMBER			
		5b. GRANT NUMBER			
		5c. PROGRAM ELEMENT NUMBER			
6. AUTHOR(S)		5d. PROJECT NUMBER			
		5e. TASK NUMBER			
		5f. WORK UNIT NUMBER			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Scripps Institution of Oceanography,,La Jolla,,CA,92093-</b>		8. PERFORMING ORGANIZATION REPORT NUMBER			
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)			
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)			
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>6</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

We also are exploring linearized methods for determining system response ranges based on an analogy to the tangent linear model and adjoint model techniques in use in Physical Oceanography. Applying these concepts to the acoustic codes may provide a computationally efficient way to compute sensitivities and transform ocean state uncertainty covariances to system performance uncertainty covariances. It may be that only an idealized reduction of the problem is attempted depending on the difficulties that are uncovered. Further, it is hypothesized that this approach may be more applicable to the total problem rather than stopping at the acoustics output because, to a certain extent, performance prediction is somewhat of a “smoothing” process, possibly enabling the required linearization mentioned above. [This work is being carried out jointly with the SAIC group.]

Uncertainty occurs in the geometry (source/receiver locations, bottom depth), the bottom properties, the surface properties (sea state and resulting bubble clouds and surface roughness), and the ocean volume (internal waves/tides, meso-scale features such as eddies, and fronts). An important member of the listed uncertainties is that due to the oceanography and how it subsequently regulates acoustic bottom interaction with uncertain geophysical parameters.

The ROMS primitive equation model is being used to simulate small-scale features in an area of interest. Separately, a simple internal wave model will be used to characterize the space-time structure of the internal wave field. In an operational scenario, we envision that both of these models will be used to predict the statistics of the oceanographic variation. The primitive equation model can both predict a deterministic environment and provide a more accurate prediction of the typical variation. The 1-D internal wave model is simple and computationally more practical but less accurate. One objective will be to compare the relative merits of these two approaches.

The existing acoustic models produce a realization of the pressure field for a single deterministic environment (which is distinct from a mean field). To capture the uncertainty, the acoustic models will need to be enhanced to rapidly produce an ensemble of pressure fields or statistics of the ensemble. The common starting point for these models is the “environmental endpoints,” i.e., the limits (or, more precisely, variances) characterizing the uncertain environment. Despite the variety of sources of uncertainty, they all can be treated using the same framework. For example, imagine a mean sound-speed profile and a lowest-order EOF characterizing the variation due to the first baroclinic mode. The “environmental endpoints” are the mean with that EOF added and subtracted based on the excursion seen in the oceanographic data. [This work is being carried out jointly with the SAIC group.]

We also expect to use the tools that we have developed to study the viability of: (a) assimilation of acoustic data from ships of opportunity (this might involve data fusion with remote sensing or the use of battlegroup location via netcentric operations) and (b) optimizing ASW area coverage in a way that reduces uncertainty by accumulating and assimilating data during operations.

Throughout the program, we have as the underlying theme and goal the construction of a methodology for capturing uncertainty in performance prediction from the overall system perspective. The focus of this work will be distilling the complexity and uncertainty of the ocean acoustic environment and the system level sensitivities to relevant situational awareness for the operator. [ORINCON is leading/coordinating this aspect of the program.]

## **WORK COMPLETED**

We have configured and run the ROMS model for a new Southern California Bight (SCB) region. Higher resolution grids are embedded within the domain of the lower resolution SCB grid that has

been run to simulate and assimilate CalCOFI data. The nesting is one-way with the boundary conditions of the inner grid taken from the larger-scale model. The higher resolution grids are off the San Diego / Tijuana coastal region in Southern California. In addition, environmental and acoustic data have been obtained from the SWellEx-96 shallow water experiment off San Diego. An objective map of the 3-D sound speed structure in the SWellEx-96 experiment region has been computed along with EOFs of uncertainty.

The formulation of the adjoint model for the Parabolic Equation acoustic model has been completed, a conference paper published [1], and a manuscript submitted [2]. This work was carried out jointly with the SAIC group.

For the purpose of better understanding the adjoint/acoustic problem, we also have derived a method for inverting one to three-dimensional sound-speed perturbations in stratified waveguide environments over ranges of several kilometers without the need for extensive numerical spatial integration. For the particular case of a range-independent ocean perturbation, a means of eliminating the numerical backpropagation and correlation steps was found to obtain a direct relationship between the error surface gradient or Frechet derivatives and the normal modes of the baseline acoustic environment. This approach can be extended to three-dimensional (range-dependent) waveguide perturbations as well. Manuscripts on this work have been submitted [3-4].

## RESULTS

The ROMS model has been configured and run with high resolution nested grids off the San Diego / Tijuana coastal region. The nesting is one-way which means that the boundary conditions of the inner grid are taken from the larger-scale model but no feedback from the inner grid is sent to the larger-scale model. Figure 1 shows the region covered by the different nested models. ROMS will be used to generate ensembles of sound speed fields for uncertainty calculations in parallel with traditional objective maps and uncertainties as described below.

The SWellEx-96 experiment was conducted off Point Loma (San Diego, CA) 10-18 May 1996 (see Figure 2a). Several acoustic arrays (two vertical arrays, a tilted vertical array, and two horizontal arrays) were deployed and recorded transmissions in the 50-400 Hz band from a variety of source tow tracks. An extensive CTD survey was carried out during the experiment and a detailed geoacoustic database exists for the region. Objective mapping of sound speed structure projected into EOF space has been carried out over the yellow shaded region. The map for the first EOF coefficient is shown in Figure 2b.

Adjoint inversion methods have been used in geophysics to derive the sensitivity of a wave field to various input parameters. With respect to the acoustic wave equation, they provide a means for computing the derivative of a received acoustic pressure field with respect to changes in environmental parameters without resorting to numerical finite-difference schemes. Adjoint theory has been combined with normal mode expressions for the acoustic field in a waveguide to derive semi-analytical expressions for the first and second-order derivatives of an acoustic field with respect to range-independent perturbations in sound speed and density as well as acoustic frequency [3]. These expressions could be used to increase the speed of convergence of local geoacoustic inversions. Expressions also have been derived for obtaining the derivative of a waveguide pressure field with respect to an arbitrary three-dimensional sound speed perturbation [4]. These expressions can be used to illustrate situations where horizontal refraction in a waveguide can arise. For example, Figure 3

illustrates the sensitivity of a 20 Hz pressure field with respect to a cylindrical sound-speed perturbation in the seafloor.

## IMPACT / APPLICATIONS

The expected impact of this project is to provide a methodology to provide a reliability measure to the operator of at-sea performance prediction models.

## RELATED PROJECTS

This is one of the programs in the ONR “Capturing Uncertainty” DRI.

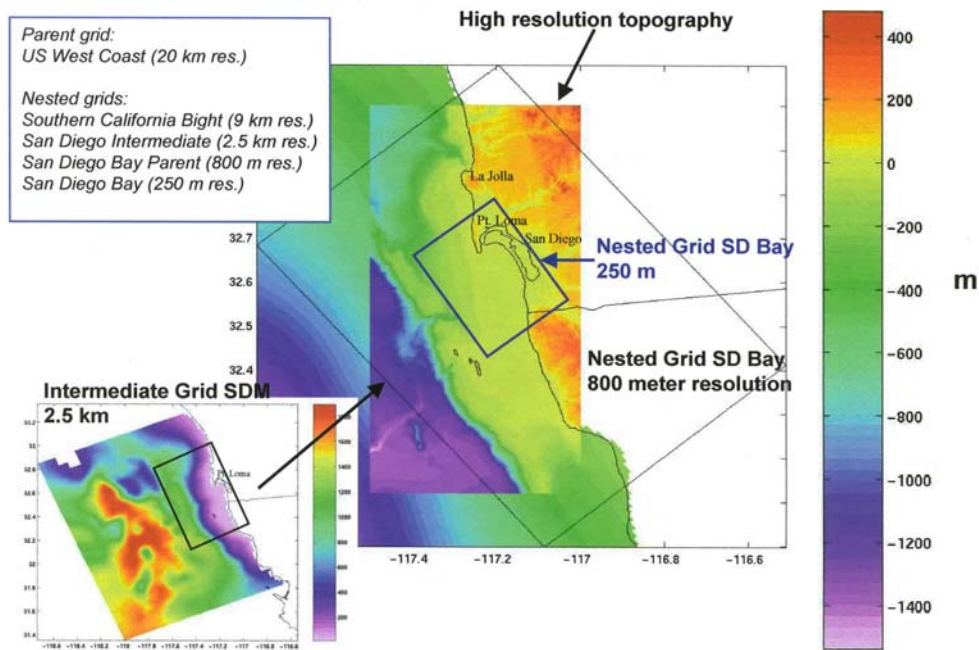
## PUBLICATIONS

[1] P. Hursky, M. B. Porter, B. D. Cornuelle, W. S. Hodgkiss, and W. A. Kuperman, “Adjoint-Assisted Inversions for Shallow Water Environmental Parameters,” in *Impact of Littoral Environmental Variability on Acoustic Predictions and Sonar Performance* Eds: Nicholas Pace and Finn Jensen, Boston: Kluwer Academic Publishers, 2002. [ISBN 0-4020-0816-3]. [published]

[2] P. Hursky, M. B. Porter, B. D. Cornuelle, W. S. Hodgkiss, and W. A. Kuperman, “Adjoint modeling for acoustic inversion,” *J. Acoust. Soc. Am.* (2003) [submitted]

[3] A. Thode and K. Kim, "An adjoint normal-mode approach for computing derivatives of pressure with respect to environmental parameters and frequency," *J. Acoust. Soc. Am.* (2003). [submitted]

[4] A. Thode, "A normal-mode formula for the derivative of a waveguide pressure field with respect to three-dimensional sound speed perturbations," *J. Acoust. Soc. Am.* (2003). [submitted]



**Figure 1. Topography for nested models in the Southern California Bight. The higher resolution grids are off the San Diego / Tijuana coastal region.**

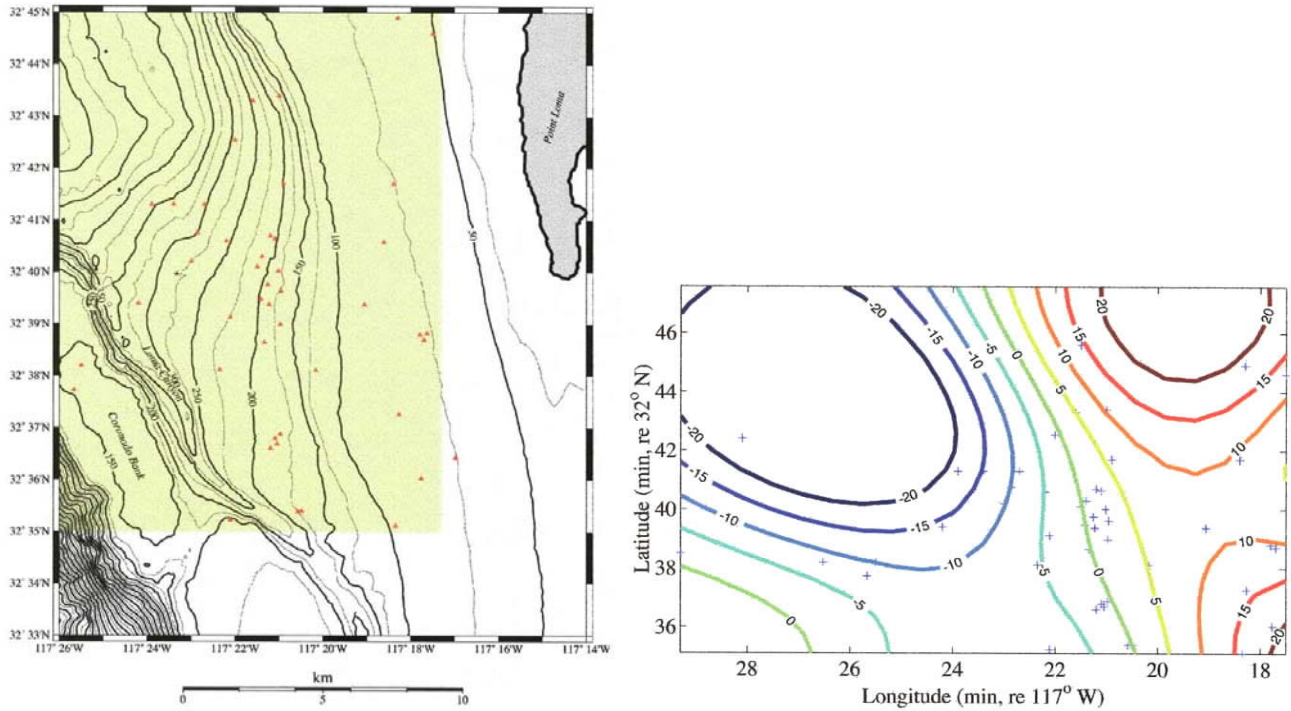


Figure 2. (a) SWellEx-96 bathymetry and location of 51 CTD casts (10-18 May 1996). (b) Objective map in EOF space of sound speed structure in the SWellEx-96 region (first EOF coefficient).

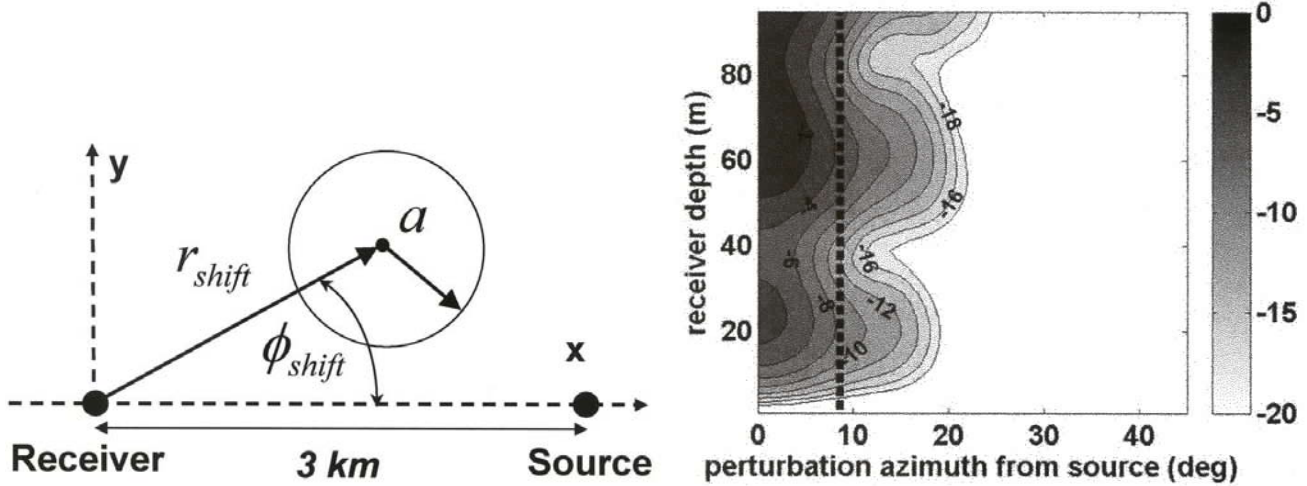


Figure 3. (a) Geometry of a seafloor cylindrical sound-speed perturbation viewed from above. The source lies along the  $x$ -axis at 3 km range from the receiver array which is placed at the origin. The perturbation radius is  $a$ , the distance from the center of perturbation to the origin is  $r_{shift}$ , and the perturbation azimuth is  $\phi_{shift}$ . (b) Effect of an ocean bottom sound-speed cylindrical perturbation on a 20 Hz acoustic field for  $r_{shift}=1$  km and  $a=150$  m. Magnitude is expressed in dB relative to  $4.5 \times 10^6$  uPa/(m/s) which yields a value of 0 dB when the perturbation azimuth is 0. The dashed vertical line indicates the perturbation angle at which the physical boundaries of the cylinder no longer intersect the  $x$ -axis. Beyond this angle, the existence of a non-zero pressure derivative indicates horizontal refraction.