Geoacoustic Inversion and the Evaluation of Model and Parameter Uncertainties

W.S. Hodgkiss and P. Gerstoft
Marine Physical Laboratory
Scripps Institution of Oceanography
La Jolla, CA 92093-0701
phone: (858) 534-1798 / (858) 534-7768 fax: (858) 822-0665
email: whodgkiss@ucsd.edu / gerstoft@ucsd.edu

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LONG-TERM GOALS

The development of new geoacoustic inversion methods, their use in the analysis of shallow water experimental data, and evaluation of geoacoustic model and parameter uncertainties including the mapping of these uncertainties through to system performance uncertainties.

OBJECTIVES

The development of new geoacoustic inversion procedures for use into the kHz frequency regime, the development of methods for estimating the entire posteriori probability densities of the geoacoustic parameters being investigated along with the mapping of these parameter uncertainties through to characterizations of applied interest (e.g. transmission loss), and the demonstration of their use in the analysis of data collected during the Shallow Water 2006 (SW06) experiment.

APPROACH

Geoacoustic inversion involves a number of components: (a) representation of the ocean environment, (b) the inversion procedure selected (e.g. genetic algorithm or simulated annealing) including the forward propagation model implemented, and (c) the estimation of uncertainties associated with the parameter estimates. The latter is critical to facilitate the mapping of these uncertainties into characterizations of applied interest including the prediction of total system performance.

Substantial experience exists in the application of full-field geoacoustic inversion methods. These have been implemented in a number of geometries (e.g. fixed vertical and horizontal arrays, towed arrays, and sonobuoys) and have been shown to work well at low frequencies (< 1 kHz). The application of these methods at higher frequencies (into the few kHz frequency regime) is at an early stage. New methods are required which are robust to modest geoacoustic heterogeneity (seafloor parameters as well as bathymetry) and temporal fluctuations (sound speed structure, surface waves, and array dynamics).

The reporting of geoacoustic parameter estimates without their associated uncertainties is of limited value. Of substantial greater utility is the complete *a posteriori* probability density (in general, the joint density between all parameters being estimated). One significant benefit of obtaining accurate *a posteriori* densities of the geoacoustic parameters is the potential to map these through to

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characterizations of applied interest (e.g. transmission loss) in order to quantify those uncertainties as well.
The Shallow Water 2006 experiment took place in July-September 2006 on the outer edge of the New Jersey continental shelf in approximately 80 m deep water. Both narrowband and broadband transmissions (source tows and stations) were made over a wide range of frequencies (50 Hz – 5 kHz) including detailed measurements of seafloor structure and water column variability. These data are available for geoacoustic inversion purposes and the investigation of how nuisance parameter uncertainty (e.g. water column sound speed variability) couples into seafloor parameter uncertainty.

WORK COMPLETED

A method for estimating transmission loss (TL) has been developed which incorporates uncertainties in the acoustic environment. Specifically, an approach has been derived and validated for the statistical estimation of TL based on the posterior probability density of environmental parameters obtained from the geoacoustic inversion process [2,4].

Participation in the Shallow Water 2006 experiment took place 23 August – 7 September 2006. Several research groups were on board the R/V Knorr (W. Hodgkiss and P. Gerstoft, SIO; D. Knobles and P. Wilson, ARL/UT; R. Chapman, U. Victoria; J. Miller and G. Potty, URI). Four array systems were deployed including two MPL 16-element VLAs and two ARL/UT SWAMI HLA/VLAs. These array systems recorded a variety of source tow and source station transmissions including CW tonal sets (50-950 Hz and 1.5-4.5 kHz), LFM chirps (100-900 Hz and 1.5-4.5 kHz), light bulbs, and combustive source transmissions.

RESULTS

Previously, geoacoustic inversion results from the ASIAEX East China Sea experiment were reported for low frequency source tow transmissions (195, 295, and 395 Hz) [1]. Subsequently, these results were used in an initial demonstration of an approach for mapping uncertainty in the geoacoustic parameter estimates into uncertainty in predicted transmission loss [2].

Quantifying uncertainty for geoacoustic parameter estimates requires estimation of the uncertainties in the data due to both ambient noise as well as modeling errors with the latter accounting for simplistic assumptions about seafloor structure, water column variability, range dependencies, etc. [3]. Both of these combine in a total error variance which describes the data uncertainty.

The observed data corresponds to a source position approximately 50 m deep and 1.7 km away from a 16 element vertical line array deployed in 105 m deep water. A total of 13 parameters (geoacoustic, geometric, and water column sound speed) were estimated in the original inversion which made use of a genetic algorithm based global optimization procedure [1]. In the initial approach, exhaustive grid sampling was used to obtain the geoacoustic uncertainties and map these to the TL domain [2]. This was feasible because only 4 model parameters (instead of all 13) were explored. However, a more realistic inversion will have a larger number of parameters. Here a Markov chain Monte Carlo (MCMC) procedure is employed in the inversion process to sample the posterior probability density of all 13 geoacoustic parameters. Then these sampled parameters are mapped to the transmission loss domain where a full multidimensional probability distribution of TL as a function of range and depth is obtained. Based on the geoacoustic inversion results, the predicted TL and its variability are estimated and then compared with the measured TL.

Fig. 1 summarizes the estimation of TL (usage domain) from ocean acoustic data observed on a vertical or horizontal array (data domain). The geoacoustic inverse problem is solved as an intermediate step to obtain the posterior distribution of environmental parameters $p(\mathbf{m}|\mathbf{d})$ (environmental domain). We are not directly interested in the environment itself but rather a statistical estimation of the TL field (usage domain). Based on the posterior distribution $p(\mathbf{m}|\mathbf{d})$, the probability distribution of transmission loss $p(\mathbf{u}|\mathbf{d})$ is obtained via Monte Carlo integration. From this TL probability distribution, all relevant statistics of TL can be obtained (e.g. median, percentiles, and correlation coefficients).

Using this procedure, Fig. 2 shows the posterior distribution of TL vs. range at 295 Hz for array El #7 (69.5 m depth). Fig. 2(a) shows the contour of the predictive distribution of TL vs. range. Gray levels represent the probability density. Darker shades mean higher probability of observing the predicted TL value. Predictive distributions at two different ranges are shown in Figs. 2(b) and 2(c) which correspond to regions of constructive and destructive interference, respectively. Since the distribution of TL is often poorly approximated by a normal distribution, the central tendency (median) and spread of the TL distribution (5th and 95th percentiles or 90% credibility interval) are indicated. Fig. 2(d) summarizes the predictive distributions by the median (heavy line) and the 90% CI (gray area). This is a practical way to convey the uncertainty in TL.

These predictive distributions are compared with actual TL observations in Fig. 3 for a source depth of approximately 50 m. The observed TL (dots) are compared with the predicted TL statistics (solid line with gray area) for the frequencies 195, 295, and 395 Hz (left to right) and for array Els #1, 7, and 16 (bottom to top corresponding to depths 99.5 m, 69.5 m, and 24.5 m, respectively). In general, there is good agreement with the percentage of observed TL data points within the credibility interval. Thus, the geoacoustic inversion statistics have captured most of the uncertainty in the environment.

IMPACT / APPLICATIONS

Geoacoustic inversion techniques are of general interest for the estimation of waveguide parameters thus facilitating system performance prediction in shallow water. Natural transition paths for these results will be SPAWAR (PMW-155) and NAVSEA (ASTO).

RELATED PROJECTS

This project is one of several sponsored by ONR Code 321OA to participate in the Shallow Water 2006 experiment and participate in the analysis of the resulting data.

PUBLICATIONS

[1] C-F. Huang and W.S. Hodgkiss, "Matched field geoacoustic inversion of low frequency source tow data from the ASIAEX East China Sea experiment," IEEE J. Oceanic Engr. 29: 952-963 (2004). [published, refereed]

[2] P. Gerstoft, C-F. Huang, and W.S. Hodgkiss, “Estimation of transmission loss in the presence of geoacoustic inversion uncertainty,” IEEE J. Oceanic Engr. 31: 299-307 (2006). [published, refereed]

[3] C-F. Huang, P. Gerstoft, and W.S. Hodgkiss, “Uncertainty analysis in matched-field geoacoustic inversions,” J. Acoust. Soc. Am. 119: 197-207 (2006). [published, refereed]

[4] C-F. Huang, P. Gerstoft, and W.S. Hodgkiss, "Validation of statistical estimation of transmission loss in the presence of geoacoustic inversion uncertainty," J. Acoust. Soc. Am. 120: 1932-1941 (2006). [published, refereed]

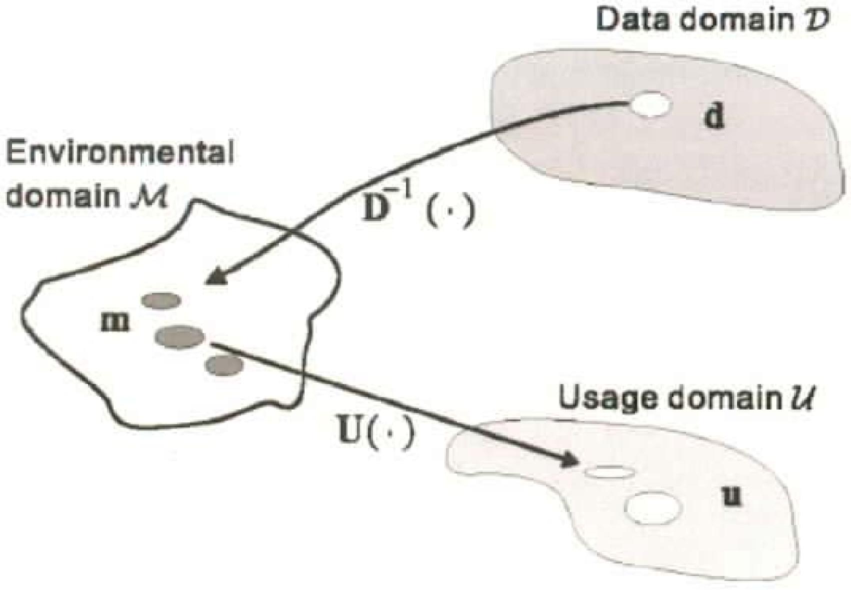

Figure 1. An observation d is mapped into a distribution of environmental parameters m that potentially could have generated it. These environmental parameters then are mapped into the usage domain.

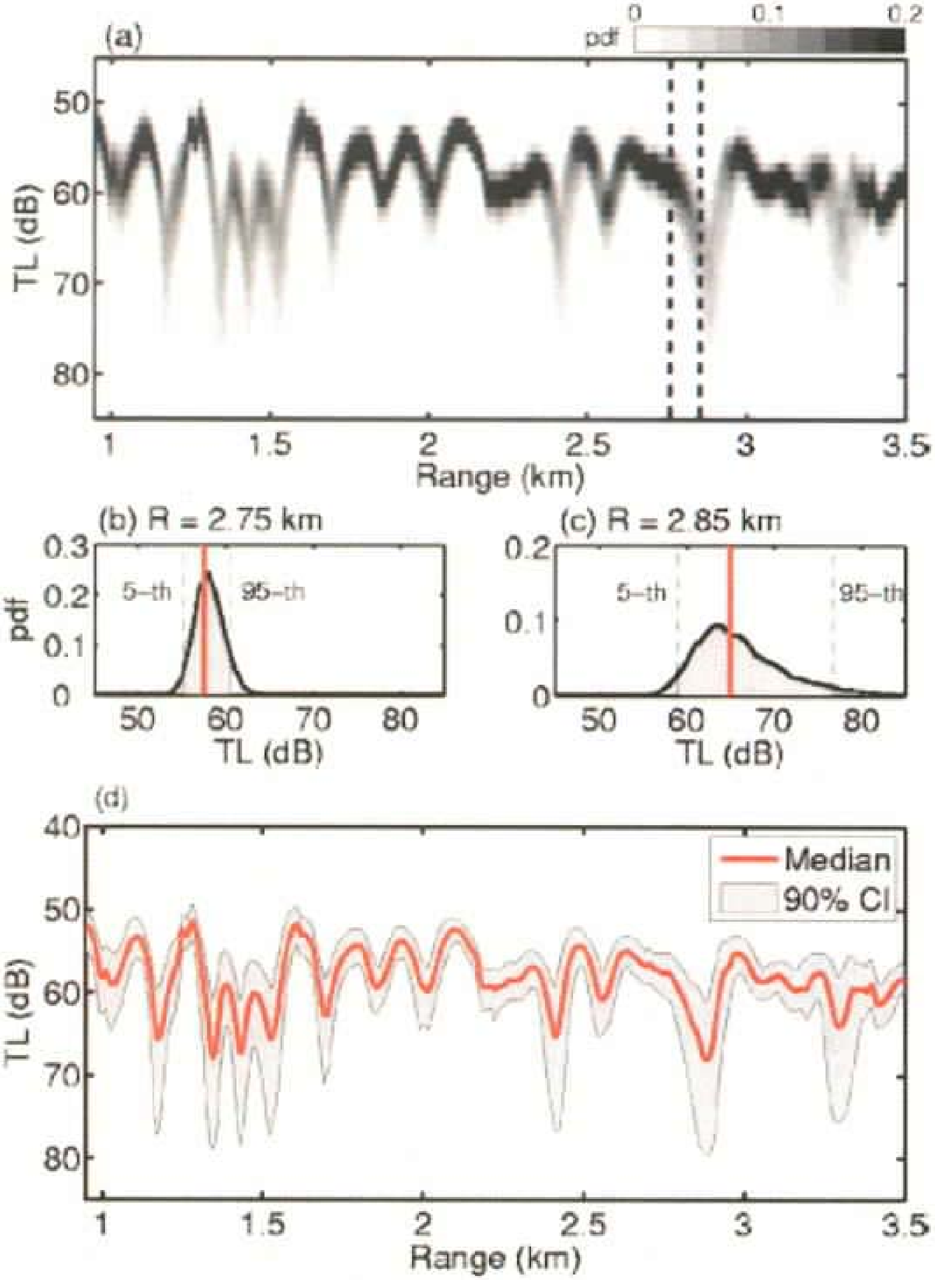

Figure 2. Posterior distribution of TL vs. range at 295 Hz for array El #7 (69.5 m depth): (a) Contour of posterior distribution for TL vs. range. (b) and (c) Posterior distributions of TL at two different ranges (2.75 km and 2.85 km). These correspond to cuts (vertical dashed lines) through the contour. (d) Statistics of the predicted TL vs. range. The solid line with gray area around shows the median and the 90% interval of the posterior distribution.

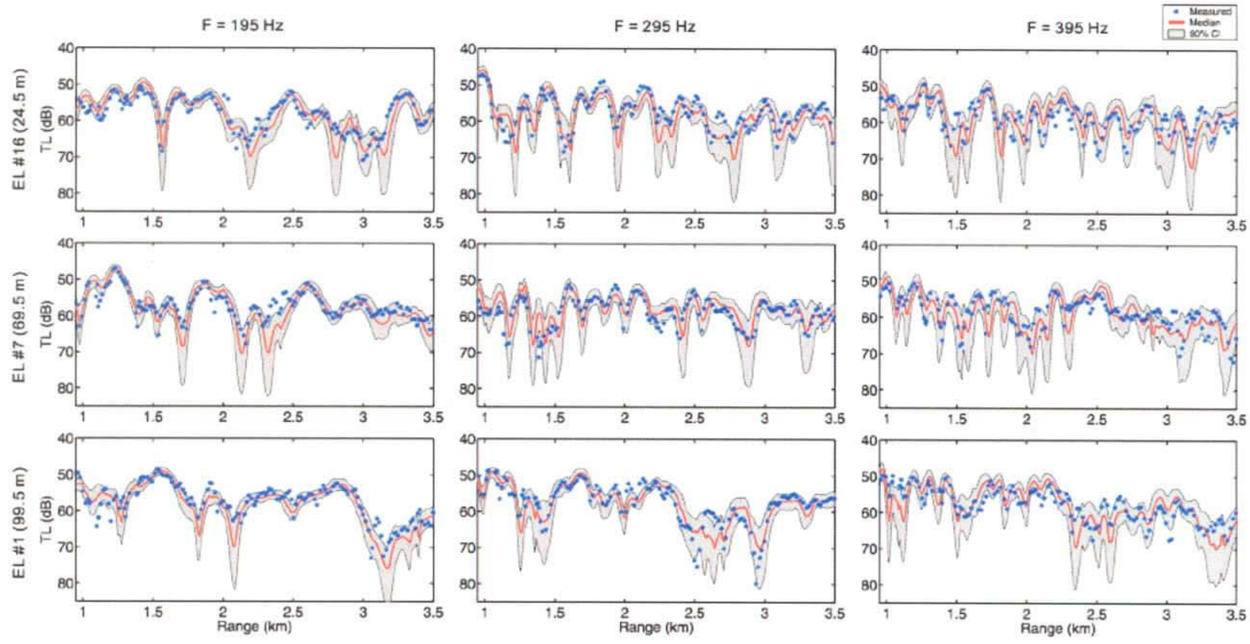

Figure 3. Predicted and measured TL (dots) for array Els #1, 7, and 16 for frequencies 195, 295, and 395 Hz. The median of the predicted TL (solid line) is shown together with the 90% credibility interval (gray area).