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4aUWb5. Acoustic interface treatment with an adjoint operator for linear range-dependent ocean index of refraction inversions

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Hursky et al. [J. Acoust. Soc. Am. 115(2), 607-619 (2004)] introduced the adjoint method and incorporated local sound-speed measurements into range-dependent ocean sound-speed inversion. They left two practical issues for the implementation of this method unresolved in this paper: the collection of appropriate environmental measurements and the implementation of bottom boundary conditions. The first of these issues was considered in a simulation study that used an oceanographic glider to collect range-dependent sound-speed measurements (Richards, CMRE memorandum (2012)). A covariance matrix was constructed from the changes observed in the range-dependent sound-speed field. The adjoint inversion was performed in a reduced element subset of the empirical orthogonal functions (EOF) base of the covariance matrix. The second issue is the focus of this paper, which describes a bottom boundary condition with a defined adjoint operator. A horizontal fluid-bottom interface is implemented using the implicit finite difference form of the parabolic equation introduced by McDaniel and Lee [J. Acoust. Soc. Am. 71(4), 855-858 (1982)]. Combined with local range-dependent sound-speed statistics gathered with gliders, this development may provide a method of near real-time acoustic measurement of ocean sound-speed variations between an acoustic source and vertical hydrophone array.

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INTRODUCTION

Acoustic inversion methods can characterize certain aspects of the marine environment in almost real time. This methodology uses an acoustic model with presumed medium properties to compute the acoustic field. Field predictions are compared with the measured field, and the presumed medium properties are modified to minimize the misfit between model predictions and observations. Different minimization algorithms such as simulated annealing, genetic algorithms or Hursky’s adjoint method [1] can be employed to solve the multi-parameter inversion problem. The first two methods mentioned are global optimization methods, which are appropriate for problems with no prior information about the answer. Hursky’s method offers a straightforward way to incorporate data gathered by using other measurement platforms. Specifically, this local optimization approach computes the gradient of a cost function of measurement and model misfit with respect to medium sound speed [2]. The performance of local optimization techniques relies heavily on the starting point of the inversion, and this may be provided by glider measurements [3].

The adjoint method is suited for measuring the range-dependent sound speed field (RDSS) from acoustic propagation measurements. This work will investigate a range-dependent bottom interface treatment that has an adjoint operator. The formulation is based on the irregular bottom treatment introduced by Lee et al. [4]. This method was chosen instead of the bottom treatment introduced by Papadakis et al. [5] used an impedance based boundary condition which removes the artificial bottom, and can include the effects of increased sound attenuation and the shear sound speed. While this implementation was shown to have an adjoint operator in [6], it requires the approximation of range dependent bottom bathymetry by a series of range independent sections, which violates energy conservation at the vertical interfaces between sections.

This work investigates the characterization of a marine environment using a glider platform and an acoustic system. Glider data was collected during the REP11 experiment, performed in the Gulf of Taranto in September 2011. This data was employed to assess the performance of acoustic inversion when coarse glider observations along the acoustic path were available.

METHODOLOGY

The adjoint inversion method used for this study closely followed the work of Hursky et. al [1]. The implicit finite difference (IFD) form of the Trappert Parabolic Equation (PE) is presented in range stepping form,

\[ B_n p_{n+1} = C_n p_n. \]  

\[ \delta p_{n+1} = F_n \delta p_n - G_n \delta u_n. \]

The matrices \( \mathbf{B} \), \( \mathbf{C} \) and \( \mathbf{F} \) are dependent on the RDSS and the grid spacing of the PE setup, while \( \mathbf{G} \) is only dependent on the zero order pressure calculated in equation 1. The square of the mismatch between this result and pressure measurements made by a hydrophone array at the final range step are used to compute a cost.

The next step of the adjoint method is to then treat each hydrophone as a source and use the adjoint operator of equation 2 to back propagate pressure mismatch from the range of hydrophones to that of the source. The field produced by this backwards propagation with the adjoint operator is used to calculated the gradient \( \nabla_u J \), or the effect of \( \delta u(r,z) \) on the cost function. The cost function is then minimized with numerical optimization routine using this gradient. At each step in the optimization, the resulting perturbation is added to the previous RDSS, which allows this method to handle small non-linear effects [1].

It is important to include accurate treatment of bottom boundary conditions in the adjoint method to model acoustic propagation in coastal waters. These bottom conditions need to be formulated in the range stepping parabolic equation, and have an analytic adjoint operator. Following the example of Hurskey et al.
[1], the initial simulation study implemented the basic Tappert narrow angle parabolic equation with no bottom or surface boundary conditions. This is the simplest treatment of the IFD, and a large body of work has been devoted to improving its accuracy since it was introduced in the 80’s [7].

There are several well-established bottom boundary conditions developed for the IFD PE, with analytic adjoint operators. The most basic of these capable of handling a range dependent interface is proposed by Lee et al. [4]. This treatment includes range dependent interfaces by using a normal derivative operator of the sloping bottom, and is used in the Trappert PE model. This formulation requires non-uniform horizontal spacing of each range step, but allows for the exact solution of the bottom interface between two fluids of different densities and sound speed. The accuracy of the seabed bottom conditions will be evaluated by comparing the forward propagation results with those of the established Range-dependent Acoustic Model (RAM). This well established model is capable of complete representation of the effects of elastic interfaces [8], and is appropriate as a reference solution.

The major focus of this work will be to show that the adjoint inversion can correctly invert for the RDSS using acoustic transmissions along a sloping bottom. The bathymetry profile used for acoustic transmission is shown in red in figure 1 and is a rough approximation of the area where the sound speed profiles were gathered. A 400 Hz source is located at 20 meters depth, above the approximately 50-meter deep thermocline, and the signal is received by a 32-element array covering the top 120 meters of 150-meter deep sea. The range-dependent sound speed field was created using statistics of this field created using measurements taken by oceanographic gliders.

**FIGURE 1:** Transmission Loss calculated using RAM. The source has a frequency of 400 Hz and is deployed at 20 meters depth.

**CONCLUSION**

The primary goal of this work is to demonstrate a bottom interface treatment with an adjoint operator that is capable of correctly including range-dependent bathymetry. This will increase the effectiveness of the adjoint method of inversion of the range-dependent sound speed field. This study will not be focused on using this adjoint treatment to invert for bottom properties, though this is a logical extension of this work and may be investigated in the future. Also, accurate bottom treatment will allow for future work to investigate optimal source depth for adjoint inversion, and the importance of source depth diversity, cited in Hursky et al. as the primary way of improving inversion accuracy [1].
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REFERENCES


