Range Limitations on Acoustic Adjoint Inversions

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***Abstract*—Measurement of range dependent ocean sound speed is an important to many ocean acoustic problems, including source localization and tomography. The recent prevalence of low cost robotic platforms such as oceanographic gliders has increased the availability of long-term measurements of the ocean environment, but in many cases their usefulness is limited by the spatial-temporal resolution of their measurements. Combining them with additional acoustic inversion sampling of the same sound speed field may increase these measurements' resolution. This paper investigates a method of combining the adjoint method, a local acoustic inversion, with glider measurements to create reliable sound speed measurements at high sampling rates. The performance of this method is found to be highly sensitive to the total range study area with a simulation study comparing root mean squared error over 30 simulated inversions. This limitation may be an effect of the limited ensonification of the water column at longer ranges, which is shown using a ray trace model.**

I. Introduction

Acoustic inversion methods are used to characterize certain aspects of the marine environment in almost real time by recreating actual acoustic measurements in an acoustic model. Many inversion schemes, based on linear and non-linear approaches, have been developed during the last decade. The adjoint inversion method has been used to measure both the range independent ocean sound speed environment, [1] and acoustic bottom properties [2]. The physical property of interest in this study is the range dependent ocean sound speed field. This property is a good candidate for estimation using inversion because it is difficult or nearly impossible to measure directly with sufficient spatio-temporal resolution for many acoustic applications. Acoustic inversion methods can potentially provide near instantaneous sampling of the ocean sound speed field, with a spatial resolution determined by the environmental parameterization chosen for the study.

The recent prevalence of low cost robotic platforms such as oceanographic gliders has increased the availability of longterm measurements of the ocean environment. Gliders can take direct measurements of the ocean sound speed, which is of interest in many ocean acoustic problems, including source localization and tomography. These glider based measurements, however, have a low spatialtemporal resolution that makes them difficult to use directly. However, these measurements have the potential to provide an accurate environmental parameterization for acoustic inversions, which could in turn be used to estimate the sound speed field at a much higher spatialtemporal resolution.

The physics of the acoustic propagation environment under study also has a significant effect on the convergence performance of the adjoint method. This paper explores the limits of environmental conditions under which the adjoint method can be expected to converge to the correct result. The adjoint method was found to be highly sensitive to the source-receiver range of the acoustic propagation in simulation studies.

II. Adjoint Inversion

Different minimization algorithms such as simulated annealing, genetic algorithms or the 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. Adjoint method 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. The performance of local optimization techniques relies heavily on the starting point of the inversion, and this may be provided by glider measurements.

The heart of the adjoint method is the adjoint operator, a linear algebra identity [3]. This operator makes the implicit finite difference parabolic equation (IFD-PE) acoustic model well suited for this method, as it simply propagates acoustic pressure along in range using a series of matrix vector products [4].

Adjoint inversions were performed in this study using synthetic acoustic data created using glider based sound speed measurements. Oceanographic observations along a 6 km acoustic transmission line were collected by a Slocum glider during the field experiment Rapid Environmental Picture 2011 (REP11), which was carried out by the NATO Centre for Maritime Research and Experimentation (CMRE) in a marine region off the western coast of the Gulf of Taranto, Italy, during October 3rd to October 10th, 2011. Each transect is constituted by approximately 25 sound speed profiles, representing a spatial resolution of 200 m. In the current study the glider profiles were assumed vertical. An interpolation grid of 5 profiles was found sufficient to capture the oceanographic variability along this transect. All of the sound speed profiles used in this study are shown together in figure 1.

The test setup used in the simulation study is shown in figure 2. This is a modification of the simulation setup used by Hursky *et al.* [1]. The source-receiver geometry assumed for the numerical simulation is shown in the figure. Source is assumed to be deployed at zero range at a depth of 100 m (well

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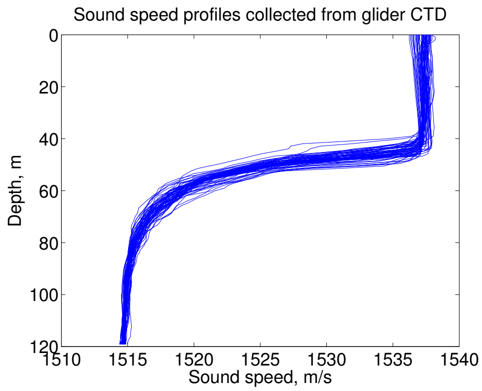

Fig. 1. Sound speed profiles taken in the Gulf of Taranto, Italy, over 13 6-km glider transits.

Environmental parameter	Value
Source frequency	400 Hz
Transmission range	4 and 6 km
Elements in receive array	32
Bottom depth	120 m
Bottom sound speed	1700 m/s
Bottom density	1.5 g/cm^3
Bottom attenuation	0.5 dB / λ

TABLE I. GEOMETRIC, SEDIMENT AND SOURCE PARAMETERS USED IN SIMULATION STUDY

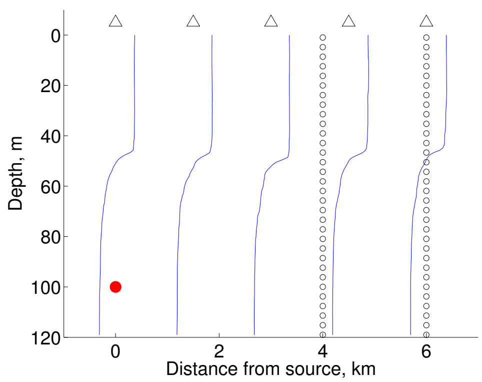

Fig. 2. Basic numerical simulation setup. The source is deployed at range 0 m and a depth of 100 m, shown as a red dot. The location of each sound speed profile is designated by a triangle along the top horizontal axis. Each circle at the range of 4 and 6 km designates an element in a 32 element array.

below the thermocline) in a water depth of 120 m. The bottom interface has been modified to include a sandy bottom, and the range was increased to 4 and 6 km. For the two different ranges considered the receivers (32 element array spanning the entire water column) are indicated in the figure at 4 km and 6 km. The parameters of the test setup are summarized in table I.

This study uses these glider measurements to provide the environmental parameterization used in the adjoint inversion method. The adjoint method calculates the gradient of a cost function describing the misfit between observed data and acoustic model predictions with respect to the ocean sound speed. This cost function is shown in equation 1.

$$J(\gamma) = \frac{1}{2}\sum_{i=1}^{M}(m_i - p_i)^*(m_i - p_i). \quad (1)$$

In this equation, measured pressure values at the hydrophone with index i is designated m_i, and the modeled pressure value is designated p_i. The asterix operator $*$ denotes the complex conjugate.

The cost function gradient calculated by the adjoint method is a measure of the way changing the sound speed at any point in the acoustic environment would affect this misfit (cost function). This cost function and its gradient information are then used as inputs to a numerical optimization routine, which efficiently finds a local minimum.

There are two challenges of this method addressed in this study; the first is restricting the search space of this inversion. Proper parameterization of the inversion will ensure that the local minimum found in the numerical optimization routine is the correct result of the inversion. This parameterization allows for the combination of the relative strengths of both methods of measuring the sound speed field, the robust direct measurement of the glider and the near instantaneous result of an acoustic inversion. A covariance matrix is created from glider measurements of the range dependent sound speed field, which is then decomposed into an empirical orthogonal function (EOF) base [5]. The mean profile and the significant EOF bases then form the search space of the adjoint method.

The procedure of the simulation study is split into three steps. First, an acoustic pressure field (at the receiver locations) is simulated using the Parabolic Equation (PE) model and a perturbed sound speed field. This sound speed field is the desired solution of the inversion method, and may be created to either follow the EOF statistics of the glider measurements or using an actual measurement. This synthetic pressure measurement is input into the inversion method as the ”measured” pressure. In the next step the adjoint method uses the mean sound speed field to calculate both the value of the cost function and its gradient for this ”measured” pressure. In the final step, this information is then input into a numerical optimization tool, which seeks to minimize the cost. The adjoint method is then linearized around this new sound speed field. These last two steps are repeated until the cost function has converged to a minimum. The sound speed field at this minimum is the result of the inversion.

The RMSE error, shown in equation 2, was used to compare the two results. The RMSE criterion for investigating inversion results is useful for observing the relative effects of environmental parameters. However, it cannot be viewed as an absolute test of the inversion performance. A more rigorous error analysis would provide a measure of the improvement to environmental understanding resulting from using the adjoint method. Identifying a specific application of the inversion results would provide a more objective rubric of performance. This would allow for the consideration of the penalty of divergent results, when the adjoint method converges to a minimum in the cost function that is unrelated to the minimum associated with the actual environmental parameters. In these cases the mean profile may be a better estimate of the environment than the adjoint result.

$$\text{RMSE} = \sqrt{\text{E}(\alpha_{ref} - \alpha)^2}. \quad (2)$$

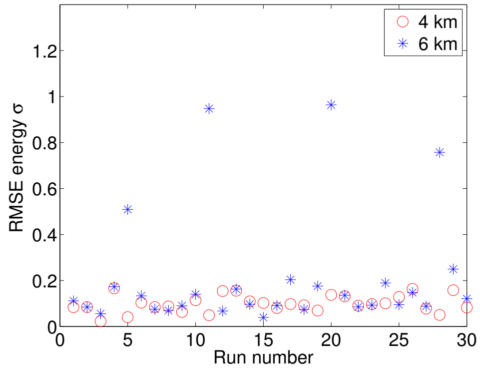

Fig. 3. Comparison of inversion results with increasing range.

III. Results and Discussion

The convergence results of simulation study are shown in figure 3, which demonstrate the strong dependence of the performance of the adjoint inversion on range. In the 4 km case the RMSE error of the all inversions was comparable to the mean RMSE of these inversions. In the 6 km transmission case there are several very significant outliers, in some cases reaching one standard deviation of scaled RMSE. The four cases where the RMSE is significantly larger than the mean RMSE value can be identified as outliers by inspection. This heuristic error criteria implies that 6 km is at the limit of the viability of the adjoint inversion method.

Figure 4 shows a ray trace representation of the acoustic propagation under study, and offers a physical explanation of the range limitations of the adjoint method. The acoustic source used in this propagation study has the same angular aperture (30 degrees) of the Claerbout wide-angle parabolic equation [6]. The area under study has a mainly downward refracting sound speed profile (as shown in the left panel in figure 4), which tends to trap the acoustical energy to sound channels deep (about 80 m) in the water column. For the first kilometer or so a significant amount of acoustic energy passes through the thermocline depth of about 50 meters, but at ranges above 4 km there is virtually no acoustic energy above the thermocline. The poor ensonification of the water column at the depths of the greatest environmental variability at long distances limits the range of the acoustic inversions.

IV. Conclusions

The adjoint method was shown to perform consistently in shortrange environments with small range dependent variations in the sound speed field. It became unstable at longer ranges, and this limitation can be linked to the physics of the acoustic propagation. Other simulation studies showed that for small propagation ranges the adjoint method was seen to be relatively insensitive to other parameters of the test setup.

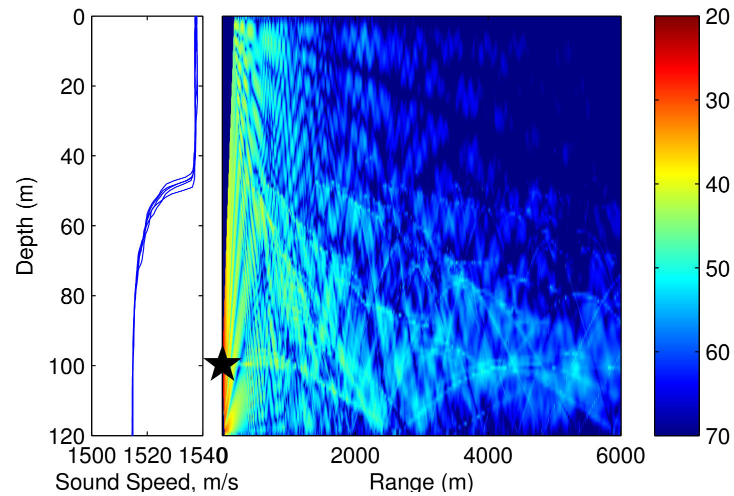

Fig. 4. Left hand panel shows the sound speed profile used in the bellhop ray trace, shown in the right hand panel.

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