INVERSION OF OCEAN ENVIRONMENTAL PARAMETERS WITH RADIATED NOISES OF AN AUTONOMOUS UNDERWATER VEHICLE: AT-SEA EXPERIMENTAL RESULTS

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Abstract: *We previously reported the results of using the radiation noise of an Autonomous Underwater Vehicle (AUV) as the sound source to invert the range-independent SSP, along with the position and velocity of the vehicle, and the water column depth. To incorporate source motion effects, the forward model based on the waveguide Doppler and normal mode theory was applied to compute the replica field, and to resolve the adjacent Doppler shifted frequencies, an analytical solution of the forward model and its simplified version were obtained for arbitrary signal integration intervals with a monochromatic source. Through simulation and lake experimental results the developed waveguide Doppler model was shown to be more effective compared with the model that does not consider the Doppler effect. In May 2014, the approach was further tested in a sea trial conducted in the area of Zhoushan Archipelago with water depth about 35m, which used a relatively large-size AUV as the moving source and a 16-element vertical line array for receiving. In this paper, the at-sea experimental results are presented. The results again show that the parameters of high field sensitivity are well estimated except those mutually-coupled which suffer from local optima. It is also observed that the mismatch in AUV trace leads to degraded matching between the measured acoustic field and the modelled one; however, owing to the clear signal tone of the AUV used, the field matching is slightly better compared to the lake test results. Extension of the current approach to range-dependent environments is also discussed.*

Keywords: *Autonomous underwater vehicle (AUV), matched-field inversion, moving source, radiated noise, waveguide Doppler*

1. INTRODUCTION

Ocean environmental parameters, such as sound speed profile (SSP), water depth, seabed properties, etc., are important parameters in determining acoustic waveguide propagation. Traditionally, a network of mooring platforms with projector/hydrophone array is deployed, sometimes combined with moving vessel nodes. Recently, as the autonomous underwater vehicle (AUV) technology matures, it has started to change the way people used to probe the ocean [2]-[5]. The AUV can be guided into areas of high uncertainty to perform small-scale high-resolution measurements of the environment.

For the purpose of inversion of ocean environmental parameters, an AUV can act as a moving receiver, a moving source, or both. For example, Holmes *et al.* [3] used a ship-deployed continuous wave source and an AUV with a towed array to obtain range-independent sediment properties; Leijen *et al.* [4] used radiated noise of an AUV received on a vertical line array (VLA) to invert the geoacoustic parameters; Chotiros *et al.* [5] used radiation noise of an AUV, in conjunction with its towed array, to measure the bottom reflection loss and obtain an estimate of the seabed type.

In a previous paper [1], we reported the results of using the radiation noise of an AUV as the sound source to invert the range-independent SSP, together with the position and velocity of the AUV, and the water column depth. To incorporate source motion effects, the forward model based on the waveguide Doppler and normal mode theory [6]-[8] was applied to compute the replica field, and to resolve the adjacent Doppler shifted frequencies, an analytical solution of the forward model and its simplified version were obtained for arbitrary signal integration intervals with a monochromatic source [1]. Through simulation and lake experimental results the developed waveguide Doppler model was shown to be more effective compared with the model that does not consider the Doppler effect. In May 2014, the approach was further tested in a sea trial conducted in the area of Zhoushan Archipelago with water depth about 35m, which used a relatively large-size AUV as the moving source and a 16-element vertical line array (VLA) for receiving. The frequency of the AUV radiation was approximately 8 kHz, which is lower compared to the small-size AUV in Ref. [1].

The remainder of the paper is organized as follows. The experimental setup is introduced in Section 2. The forward acoustic model based on the waveguide Doppler model and the objection function of the inversion problem are briefly reviewed in Section 3. Inversion results with experimental data are presented in Section 4. Finally, Section 5 concludes the paper.

2. EXPERIMENT AND DATA DESCRIPTION

The experiment was conducted in the area of Zhoushan Archipelago with water depth about 35m, in May 2014. The vehicle uses a GPS, with an accuracy of about 10 m, for surface navigation, and uses dead reckoning when diving. A detailed description of the vehicle can be found in Ref. [9]. The geometry of the experimental area and the trajectories of the vehicle are shown in Fig. 1. The AUV started its run from point ‘Start’ with constant depth of 5 m at a speed of 1.5 m/s, and then tracked points P1, P2, and P1 in sequence.

During the experiment, SSPs were measured near the location of VLA by CTD, served as a database for the computation of the empirical orthogonal functions (EOFs) [10]. The first 3 EOFs describe 97.1% of the sound speed variation in terms of energy. The 16-element VLA and the data acquisition system are the same as that in Ref. [1]. The depth of the 1st element was measured to be 2.65 m.

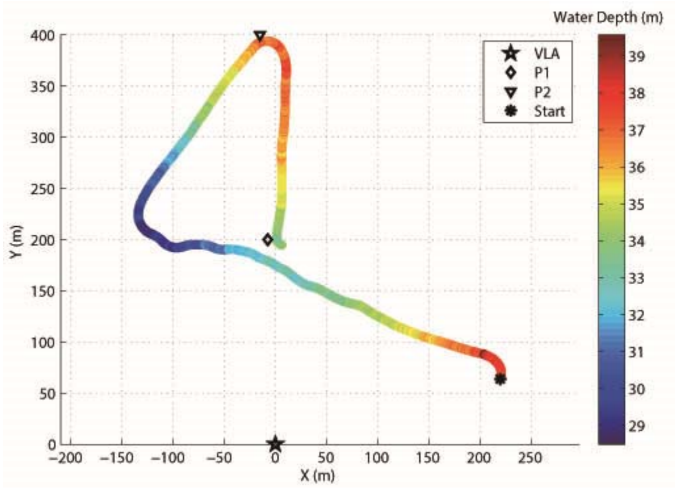

Fig. 1: Trajectory of AUV and the water depth along the trajectory.

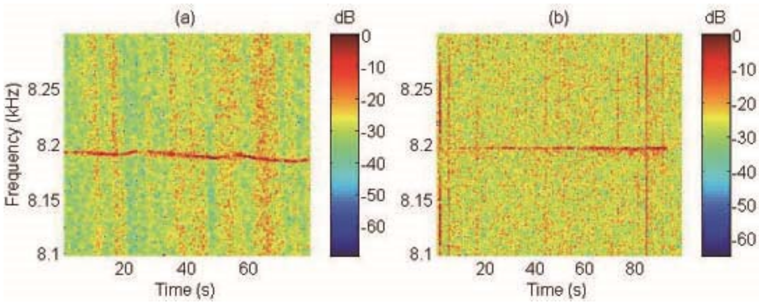

Fig. 2: Spectrogram of the radiated noise in the mission. (a) The received data from point (100 m, 125 m) to (0 m, 175 m) (see Fig. 1); (b) The received data from point (10 m, 350 m) to (0 m, 200 m) (see Fig. 1).

Fig. 2 shows the spectrogram of the signal received by the 5th element of the VLA. Fig. 2 (a) shows the spectrogram of the mission [see Fig. 1] from point (100 m, 125 m) to (0 m, 175 m). Fig. 2 (b) shows the spectrogram from point (10 m, 350 m) to (0 m, 200 m) where the radial velocity was approximately 1.5 m/s.

3. THEORY

The inversion is based on matched-field processing, and the process involves a forward acoustic model to predict the received acoustic field and an objective function to be optimized. EOFs are employed to reduce the degrees of freedom of SSP.

Parameter estimation is carried out by maximizing the normalized Bartlett power objective function of the form

$$B(\mathbf{x}) = \frac{1}{N_Q} \sum_{q=1}^{N_Q} \frac{\left|\mathbf{h}_q^H \mathbf{d}_q\right|}{\left\|\mathbf{d}_q\right\| \left\|\mathbf{h}_q\right\|} \tag{1}$$

where:

- $0 \leq B(\mathrm{x}) \leq 1$, and a perfect match between the measured acoustic field and modelled acoustic field is found when $B(\mathrm{x}) = 1$;
- x denotes the environmental parameters to be estimated;
- $\mathrm{h}_q = [\tilde{p}(\mathrm{r}_0, z_1, \omega_q) \cdots \tilde{p}(\mathrm{r}_0, z_m, \omega_q) \cdots \tilde{p}(\mathrm{r}_0, z_M, \omega_q)]^T$ is the modelled acoustic field or replica field calculated at receiver frequency ω_q, M is the number of elements of the VLA, N_Q is the number of receiver frequencies to be used, and r_0 is the source-receiver range;
- d_q is the measured acoustic field vector of the VLA at receiver frequency ω_q;
- $(\cdot)^H$ denotes the conjugate transpose of a matrix, $|\cdot|$ denotes the modulus of a complex number, and $\|\cdot\|$ is the Euclidean norm of a vector.

There are three models of replica field mentioned in Ref. [1]. Considering the computational complexity and the performance, this paper uses model M2 to compute the replica field. M2 can be expressed as [1]

$$\tilde{p}(\mathrm{r}_0, z, \omega) \approx \sum_{l=1}^{L} \frac{2e^{-i(\omega-\omega_r^l)T/2}\sin[(\omega-\omega_r^l)T/2]}{\omega - \omega_r^l} \psi(\mathrm{r}_0, z, \omega, k_{rl}) \quad (2)$$

where T represents the signal integration interval, ω_r^l is the Doppler shifted frequency, and L is the number of Doppler shifted frequencies. $\psi(\mathrm{r}_0, z, \omega, k_{rl})$ is the pressure value evaluated at receiver frequency ω and wavenumber k_{rl}.

4. EXPERIMENTAL DATA ANALYSIS

The data around the point (0 m, 230 m) in Fig. 1 are used for processing, when the AUV was moving toward the VLA. Fig. 3 shows the received power spectral density for source frequency of 8187.8 Hz when signal integration interval T=5 s. The source level was estimated to be 120 dB re 1 μPa @ 1 m. Fig. 4 shows scatter plots illustrating the parameters sampled during genetic algorithms (GA) inversion with single frequency 8195.2 Hz. The maximum matched value is 0.69 which is not that good, since there is mismatch in AUV trace, which leads to degraded matching between the measured acoustic field and the modelled one.

From the scatter plots, we can see that EOF coefficients (a_1, a_2, and a_3), source velocity v_s, and source frequency f_s have relatively good estimated results. The reference value of water depth D is the depth around the point (0 m, 230 m), while the estimated value is the average water depth between VLA and point (0 m, 230 m). From Fig. 1 we can see that the average water depth is smaller than the water depth around point (0 m, 230 m). Thus the estimated value is smaller than the reference one. The reference value of range r_0 is derived from dead reckoning, which has accumulated errors. When the AUV floated up, the range using dead reckoning was 20 m larger compared with the GPS, which is coincide with the estimated result. The estimated source depth z_s and the depth of the 1st element of VLA z_1 are slightly biased compared with the respective reference values. One reason can be that the source depth is coupled with z_1. The other possible reason is that there is a measurement error of z_1 using the depth sensor.

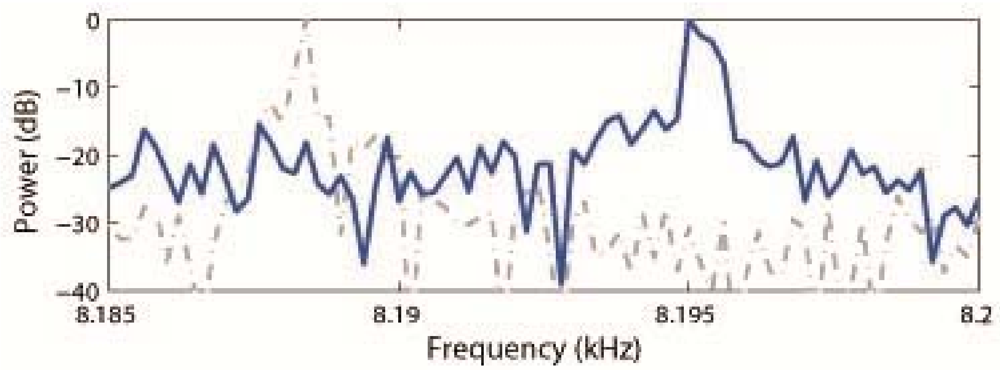

Fig. 3: Power spectral density of the data around the point (0 m, 230 m) when T=5 s. Dash-dotted line is the power spectral density when the radial velocity was approximately zero.

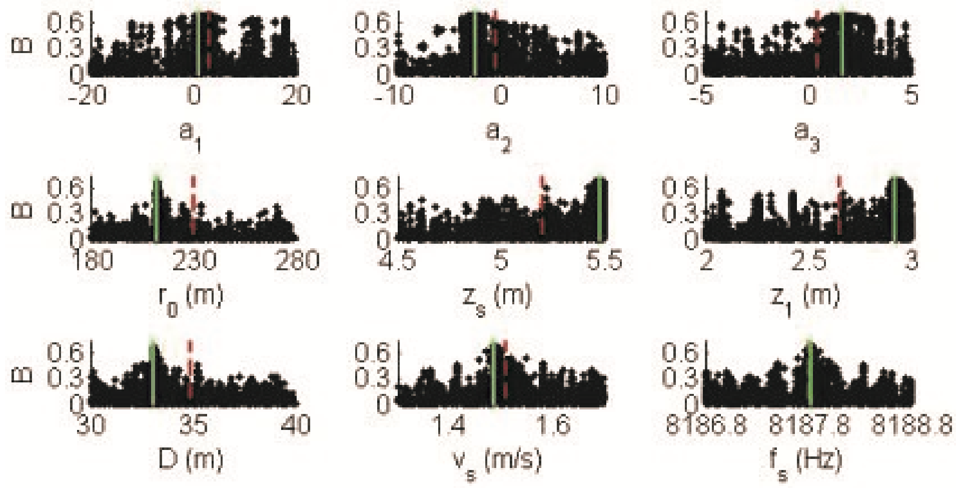

Fig. 4: Scatter plots of GA search using M2 at T=5 s with single frequency of 8195.2 Hz. The dashed line indicates the reference value, and the solid line indicates the final inversion result.

5. CONCLUSION

In this paper we use the radiation noise of an AUV as the sound source to invert the range-independent ocean environmental parameters and present the at-sea experimental results which involve a simplified waveguide Doppler model. The parameters of high field sensitivity are well estimated except those mutually-coupled. The results further demonstrate the effectiveness of the developed approach in Ref. [1].

For further effort, we can use state-space model to invert range-dependent ocean environmental parameters along the AUV trajectory. Note that at each point of the track, the estimate is the average from the source to the receiver; by doing the inversion sequentially with AUV moving, one can get the parameter estimate at individual points (sections). This process is equivalent to iteration over space, while iteration over time is considered as a solution to an under-determined inverse problem.

6. ACKNOWLEDGEMENTS

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