THE SEA EXPERIMENT FOR GEOACOUSTIC PARAMETERS INVERSION WITH COMPRESSIVE SENSING

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Abstract: *In shallow water environments, geoacoustic parameters are important to predict the performances of sonar systems. In this paper, a compressive sensing (CS) based spatial-temporal approach is proposed to invert the geoacoustic parameters. The channel impulse response is sparse in time domain, thus CS is exploited to estimate the arrival times of different paths, which offers a super resolution in estimating the arrival times. With the estimated arrival times of multipaths received by a vertical linear array (VLA) via CS, the geometry and geoacoustic parameters can be determined. A sea experiment was carried out for evaluating the effectiveness of the CS based spatial-temporal inversion approach. The analysis of experimental data gives us encouragement.*

Keywords: *Compressive sensing, vertical linear array, arrival time analysis, geoacoustic inversion, sea experiment*

1. IINTRODUCTION

In shallow water environments, the geoacoustic parameters can be utilized for evaluating the performance of sonar system. However, it is difficult to directly measure the geoacoustic parameters. Thus, inversion is one of the effective methods for achieving the geoacoustic parameters. By deploying a vertical linear array (VLA) spanning the water column or a towed horizontal linear array (HLA), using a controlled acoustic source or ship noise as the source, the geoacoustic parameters can be inverted using matched field inversion (MFI) [1-2], modal dispersion techniques [3-4], arrival time analysis [5-6] and etc.

In this paper, a compressive sensing (CS) [7] based spatial-temporal geoacoustic parameters inversion approach is proposed. A controlled acoustic source transmits the broadband signals, and a VLA or a HLA receives the signals carrying the information of the environment. Assume that there is a short range between the source and the receive array, then the channel responses contain several waterborne reflected paths along with several sediment's reflected paths arrived at different times. Consequently, the channel responses are sparse in time domain. CS can be therefore applied to estimate the relative arrival times of different paths with super resolution. With the estimates of relative arrival times of different paths, the geometry parameters (e.g. the relative range) and geoacoustic parameters (e.g. sediment compressional speed and thickness) can be calculated. Since CS offers the precise estimates of the relative arrival times, the uncertainties of the subsequent estimated geoacoustic parameters decrease.

The paper is organized as follows: Section 2 presents the CS based spatial-temporal inversion approach; Section 3 introduces the sea experiment in Zhoushan and the analysis of the experimental data; Section 4 gives conclusions.

2. INVERSION APPROACH

In [6], the arrival times of multipaths are estimated by CS which has higher resolution than that by matched filtering. The geoacoustic parameters are then estimated using data received by a HLA. Here, the inversion scheme is applied to a VLA within short ranges. Considering a shallow water environment geometry shown in Fig. 1, the channel impulse response of each array element is dominated by several acoustic paths: direct path, surface reflected (SR) path, bottom reflected (BR) path, sediment bottom reflected (sBR) path and other multiple reflected waterborne paths. Multiple reflections within one sediment are neglected due to the bottom loss. The arrivals of the sBR paths are slightly behind the arrivals of BR, and their amplitudes are less than the waterborne paths.

The depths of source and the VLA are usually recorded by temperature-depth sensors (TDs). The ranges are calculated according to the GPS data of the source and the receive array. However, there are large uncertainties in estimating the ranges due to the error of the GPS device, the drifting of the source or the receive array due to ocean currents, the tilt of the VLA and etc. Suppose that the depths of the source and the receive array are known, the ranges are revised by the differences of the waterborne paths. According to the image method [9],

$$\left(\hat{t}_{SR} - \hat{t}_{direct}\right)c_0 = \sqrt{r^2 + (z_r + z_s)^2} - \sqrt{r^2 + (z_r - z_s)^2}, \tag{1}$$

where $\hat{t}_{direct}$ and $\hat{t}_{SR}$ are the time estimates of the direct and SR paths using CS, z_r and z_s are the depths of the receive array and the acoustic source, respectively, r is the relative range between the receive array and the acoustic source. For an environment with the irregular sound speed profile (SSP), the travel paths bend, the ray codes should be developed instead of solving Eq. (1).

Since the relative range between the source and VLA is short, range independent assumption is reasonable, where the seafloor is assumed to be flat and one or several homogeneous sediment(s) lay upon a half space basement. The water depth can be obtained using a conductivity, temperature and depth sensor (CTD) along with the SSP.

Suppose that the sBR arrivals are estimated with the VLA, combining these arrivals, the sediment's compressional speed c_1 and thickness h_1 can be solved jointly. The objective function is defined by

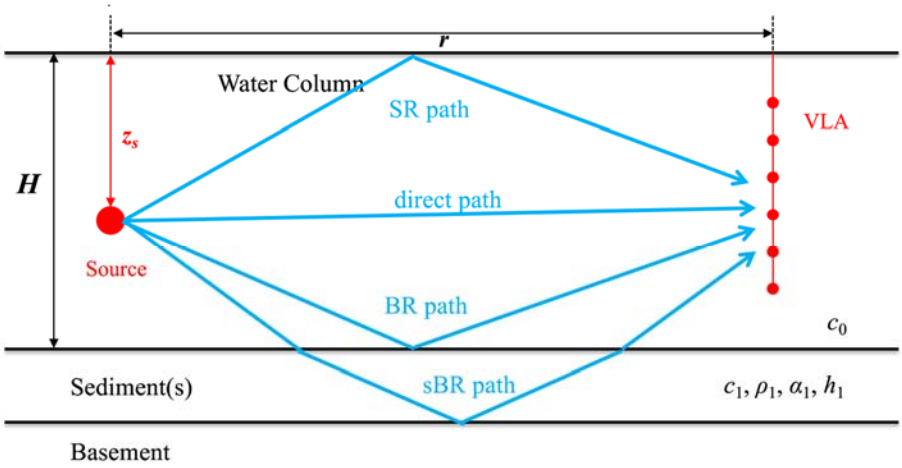


Fig. 1 Geometry of the shallow water environment and illumination of dominant paths: direct paths, surface reflected (SR) paths, bottom reflected (BR) paths and sediment bottom reflected (sBR) paths.

$$E(c_1,h_1) = \sum_{n=1}^{N} \left| \hat{t}_n - t_n(c_1,h_1) \right|^{\alpha}, \tag{2}$$

where $\hat{t}_n$ is the estimate of arrival time of sBR path of the *n*th array element, $t_n(c_1,h_1)$ is the theoretical arrival time of sBR path with given c_1 and h_1 of the *n*th array element calculated using image method. *N* is the number of the array elements. α is the positive power, here $\alpha=0.2$. With c_1 and h_1 closer to the true values, smaller $E(c_1,h_1)$ is obtained. Global optimization algorithm is not needed since only two parameters to be solved, the grid research with once refinement is adopted in this paper.

3. SEA EXPERIMENT AND DATA ANALYSIS

3.1. The experiment description

For evaluating the effectiveness of the CS-based geoacoustic inversion approach, an experiment was carried out on December 20, 2016, in ocean area near Liuheng Island, Zhoushan, China. The water depth of experiment site was about 21m, and the SSP was nearly isospeed as shown in Fig. 2. The SSP was measured with a CTD during the period of the experiment twice as the blue and green lines. The variation of the SSP was less than 1m/s. And the red line indicates the mean SSP which is used in the data analysis.

A middle frequency acoustic source was suspended from a ship to a depth of 12.3 m which is measured by a temperature and depth (TD) sensor attached to the acoustic source. The ship was moving with a small speed driven by ocean currents. According to the trajectory of the ship, the speed of the acoustic source was less than 0.4m/s. The transmitted signal is a 1.8~5.8kHz LFM signal weighted by a Hanning window with duration 1s repeated every 1s.

A 16-element VLA with spacing of 1m was deployed to cover the water column from 3.5 to 18.5m which is measured by two TDs fixed at two ends of the VLA. According to the GPS， the VLA was located at (122.1606°E, 29.7547°N) during the experiment. The signals received by the VLA were amplified first and then sampled with the sampling frequency 48kHz, stored in double precision format (64bits).

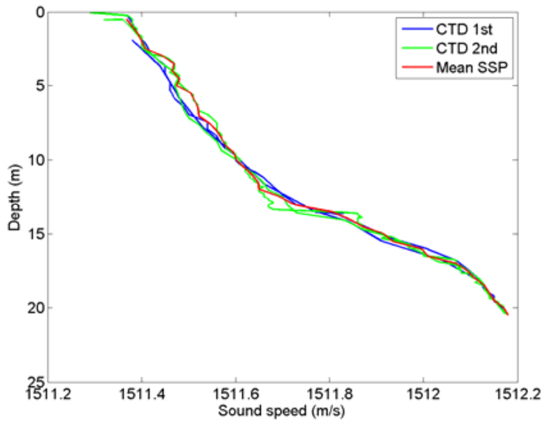


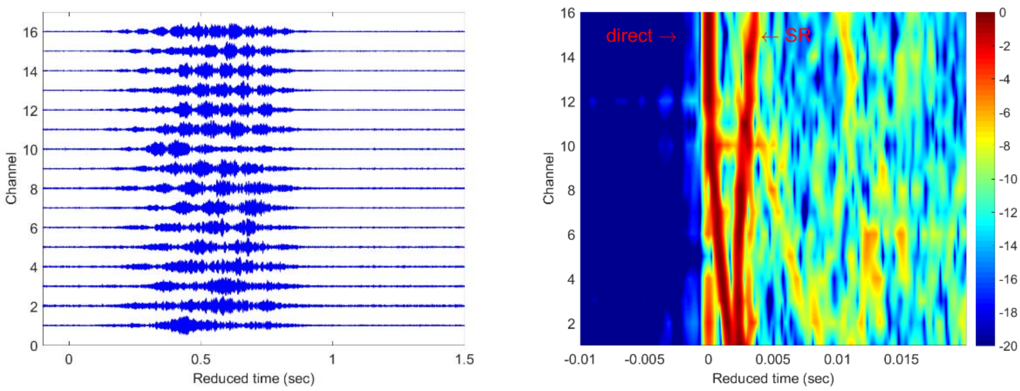
Fig. 2 The measured SSPs (blue and green) and mean SSP (red) of the experiment site. The SSPs were measured near the VLA.

3.2. Experimental results

One snapshot of the received signals is truncated and analyzed with the proposed inversion approach. The received pulses of the VLA and corresponding matched filtering outputs are shown in Fig. 3.

The two red curved peaks indicate the direct and SR paths, respectively. The range between the source and the VLA is 75.11m calculated with the GPS recordings. Because the range is short, only reflections with small grazing angles are observed in Fig. 3.

The arrival times of multipaths are then achieved by CS. The frequencies are 2500: 20: 5500Hz, the time grid step is 0.02ms. The arrival times and the corresponding amplitudes are shown in Fig.4. It is seen by comparing Fig.4 with Fig. 3 (b) that CS achieves a much higher resolution. The time differences between the direct and the SR paths are used to revise the range using Eq. (1). And the estimate of the range is 79.12±4.55m, which is consistent with the true range.



(a) (b)

Fig.3 (a) One snapshot of the received time series of the VLA and (b) the corresponding matched filtering outputs. The received time series and matched filtering outputs of each channel are normalized. The matched filtering outputs are taken logarithm.

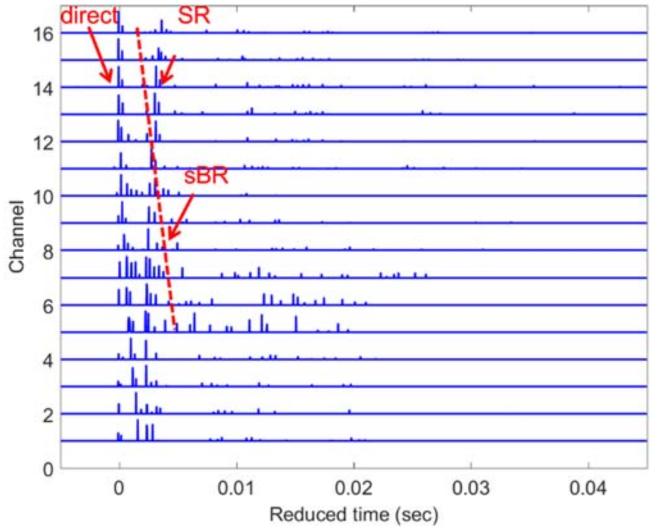


Fig. 4 CS outputs of the received time series, the amplitudes of each channel are normalized and multiplied by 0.8. The red oblique dashed line indicate the arrivals of sBR paths.

From Fig.3 and 4, only arrivals of one sediment are observed, thus it is reasonable that a two-layer sediment model is assumed for the sea bottom. The arrival times of sBR paths are determined by the sediment's compressional speed and thickness, and are irrelevant with the density and attenuation. With the arrivals of sBR paths detected from Fig. 4, the ambiguity surface with respect to c_1 and h_1 is shown in Fig. 5. The intersection of the two white dashed lines indicates the final estimated sediment parameters: $\hat{c}_1 = 1534.6$m/s, $\hat{h}_1 = 6.65$m.

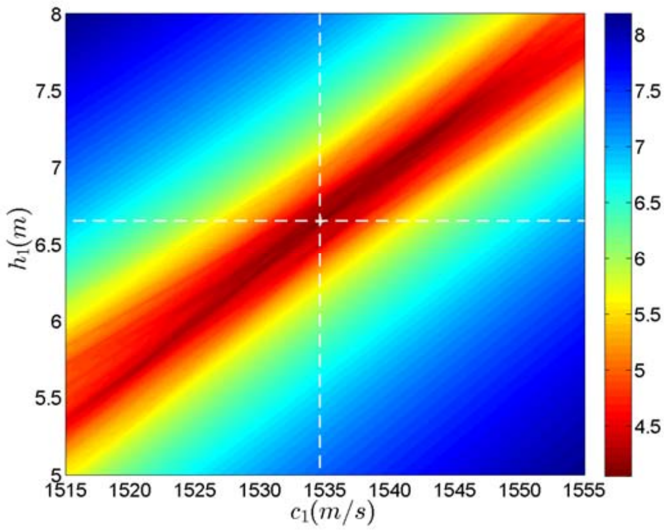


Fig. 5 The ambiguity surface after once grid refinement of sediment's compressional speed and thickness using 2-dimension grid search, Eq. (2) is the objective function with α = 0.2. The intersection of the two white dashed lines indicates the final estimated sediment parameters: $\hat{c}_1$ = 1534.6m/s, $\hat{h}_1$ = 6.65m.

4. CONCLUSIONS

A CS based spatial-temporal approach for geoacoustic parameters inversion was evaluated by a sea experiment in Zhoushan, China. A VLA was utilized to receive the broadband signals transmitted by a slowly moving acoustic source. With experimental data and the assumption of a two-layer sediment model, we have achieved the estimates of sediment's compressional speed 1534.6m/s and thickness 6.65m by the proposed CS inversion approach.

5. ACKNOWLEDGEMENTS

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