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Basic at-sea experiment for long horizontal time-reversal communication in deep ocean

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In our program, research and development on a long cruising autonomous underwater vehicle (AUV) are promoted. In such AUV operation, it is very significant to establish acoustic communication even at low data-transmission rate. Time-reversal techniques have a possibility to realize such long horizontal communication, which converge multipath signals to the focus, decrease intersymbol interference (ISI). We have researched on time-reversal communication in the deep ocean and have proposed a method of combining time reversal and adaptive equalizer. To verify the performance of such time-reversal communication, at-sea experiments, at the range of 20, 30 and 40 km in the Suruga trough, and 100 km at a water depth of 4000 m in outer ocean, were executed following our first experiments. In these experiments, the convergence of a probe pulse by passive time reversal is confirmed, and based on these converged pulses, time reversal communication performance is investigated. Similar performance analysis, using experimental data of ocean acoustic tomography over 1000 km, and simulations at the range of 1000 km are also executed. In these results, it is verified that time reversal is superior to conventional methods.

1 Introduction

In Japan Agency for Marine-Earth Science and Technology (JAMSTEC), the research on underwater acoustic technologies is assigned to our research group and researches on time-reversal technique have been promoted especially for long horizontal communication.

In our program, an autonomous underwater vehicle (AUV) for long cruising in the deep ocean has been developed [1,2]. It will be very significant to communicate with such AUV for remote controlling even at low data rate. Time-reversal technique has the possibility to achieve such long horizontal communication by utilizing the multipath signals and reducing intersymbol interferences (ISI) [3-15].

The effectiveness of time reversal communication in the deep ocean was demonstrated in our first experiment [16,17]. In this paper, the results of subsequent basic at-sea experiments at longer ranges, up to 100 km, are described. And the performance was verified at the range of 1400 km using experimental data of ocean acoustic tomography data executed in JAMSTEC.

2 Time reversal communication

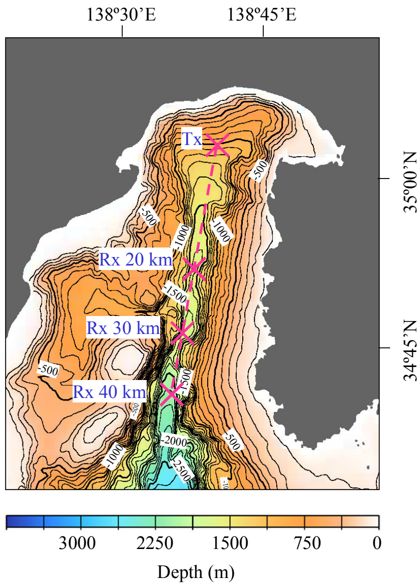
Recently, time-reversal communication in shallow water has been studied by many researchers [3-7]. By time reversal, multipath signals are converged in time and space, so that ISI are reduced and communication can be achieved. Time reversal can be used for bi-directional communication. In case of multiple-input-single-output (MISO), it is called active time reversal and, in case of single-input-multiple-output (SIMO), it is called passive time reversal. Due to limitation of the ship-time, only PTR measurements were executed in the experiments described in this paper. Because they are equivalent theoretically, the results can be regarded as the performance prediction of ATR as well as PTR.

In these our experiments, projectors, PS-500D manufactured by Engineering Acoustic Inc., are used as sources, whose center frequency is 500 Hz and bandwidth is +/- 10 %.

3 Experiment Scheme

3.1 Experiment at ranges of 20 to 40 km

Our first experiment of bi-directional time reversal communication was executed at the range of 10 km in the Suruga-bay [16,17]. The second experiments (EXP2) were executed along the axis of the Suruga-Trough at the ranges of 20, 30 and 40 km, as shown in Fig. 1. The source was moored at the depth of 1,000 m and the receiver was suspended from the research vessel while changing its depth in order to compose a virtual receiver array. Such receiving positions are shown in Fig. 2 with the sound velocity profile.



.Fig. 1. Experiment sites of EXP2.

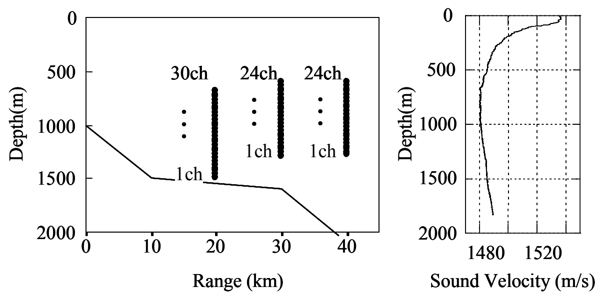


Fig. 2. Receiving points and sound velocity profile of EXP2.

3.2 Experiments at range of 100 km

The third experiment (EXP3) was executed at the site shown in Fig. 3, at the range of 100 km. The source was moored at the depth of 1000 m, the receiver was suspended from the research vessel. Thus signals are measured at the depth from 850 to 1000 m at the intervals of 5 m approximately. Thus, the transmission was executed near the SOFAR axis. The sound velocity profile and the receiving points are shown in Fig. 4.

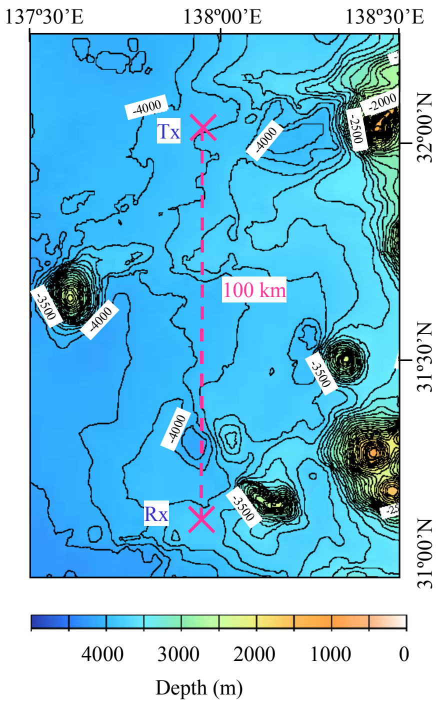


Fig. 3. Experiment sites of EXP3.

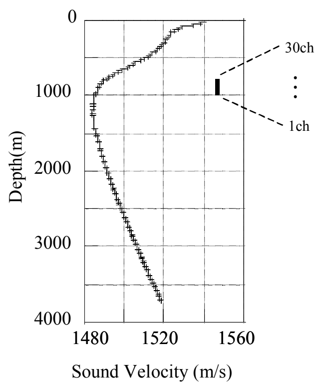


Fig. 4 Sound velocity profile and receiving points of EXP3.

3.3 Experiments at ranges over 1000 km

In JAMSTEC, experiments of Ocean Acoustic Tomography (OAT) were executed four times from 1997 to 2001 [18,19]. In these experiments, 200 Hz projectors were used, and the 10 or 11 orders M-sequence signals were transmitted. The experiment sites and the sound velocity profiles are shown in Fig. 5 and 6, respectively. These experimental data can be used for performance analysis of time reversal. From these data, not saturated signals are picked up and processed by PTR. In this paper, the results of using signals from TJ1 to TJ5, as indicated in Fig. 5, at the range of 1450 km, are described. In these experiments, the source and the receivers are moored at the depth of 1100 m approximately, that is, near the SOFAR.

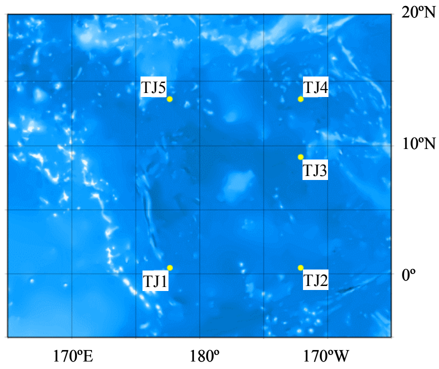


Fig. 5. Experiment sites at the range over 1000 km.

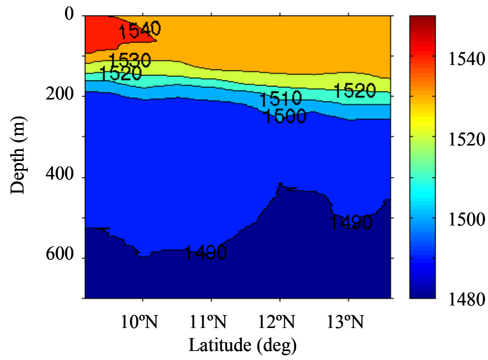


Fig. 6. Sound velocity profile at the site shown in Fig. 5.

4 Experiment results

4.1 Pulse convergence by time reversal

To confirm time-reversal focusing, received signals are compared with the signal converged by PTR. In EXP2 and 3, a chirp signal is transmitted as a probe signal, whose length is 2.0 s and sweep bandwidth is from 475 to 525 Hz.

In Fig. 7, signals received at the array in EXP2 shown, in which many multipath signals are observed. They are absolute envelopes after chirp correlation. In the meantime, signals converged by PTR are shown in Fig. 8. These figures show that time reversal can converge multipath signal and produce clear pulses.

The signals measured at the array and the signal converged by PTR in EXP 3 are also shown in Fig. 9 and 10, respectively. These results show that time reversal can converge multipath signals also at the range of 100 km.

In EXP 2 and 3, the ship position was tried to be kept as constant as possible, however, it was drifted at 10.0 or 20.0 m per minute during the measurement at each depth. In addition, the heaving of the ship causes the depth fluctuation of the receiver. Those movements violate the prerequisite for time reversal, such influences are included in these results.

As mentioned above, signals from TJ1 to TJ5 at the range over 1000 km in OAT experimental data are used for performance analysis of time reversal. In these experiments, signals are measured at every three hours for a year. These signals are changed due to environment change, so that they can be used for multichannel communication using the diversity in time as well as in space.

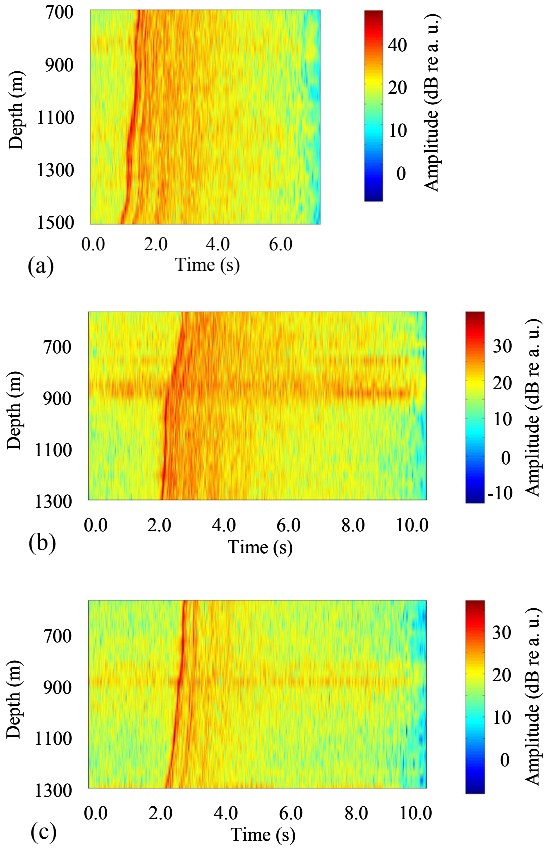


Fig. 7. Signal received at the ranges of (a) 20 km, (b) 30 km and (c) 40 km.

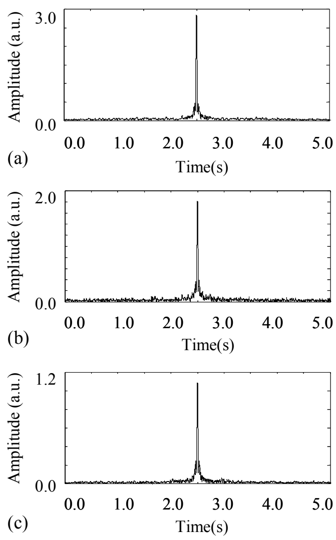


Fig. 8. Signals converged by PTR at the ranges of (a) 20 km, (b) 30 km and (c) 40 km.

In a long cruising AUV operation, signals are transmitted successively from a base station and AUV receives those signals at different positions while moving horizontally at a constant speed. Then, it is possible to achieve communication with spatial diversity using changing signals received at different positions, that is, a virtual horizontal array. So the analysis using OAT experimental data can be used for performance prediction with time diversity instead of space diversity. Similar analysis are also performed in [20].

Here, thirty signals, which are not saturated, are picked up, and some of these signals are shown in Fig. 11. These thirty signals are processed by PTR like as signals received at thirty channels horizontal array. The signal converged by PTR are shown in Fig. 12. As previous results, many multipath signals are received and converged well by PTR.

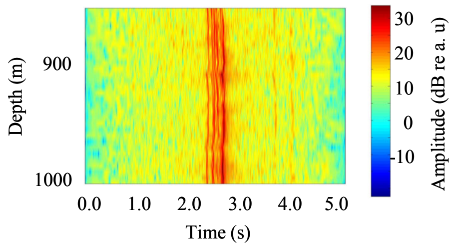


Fig. 9. Signal received at the range of 100 km.

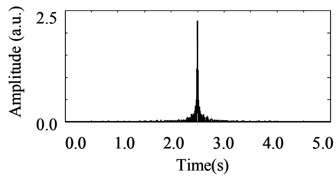


Fig. 10. Signal converged by PTR at the range of 100 km.

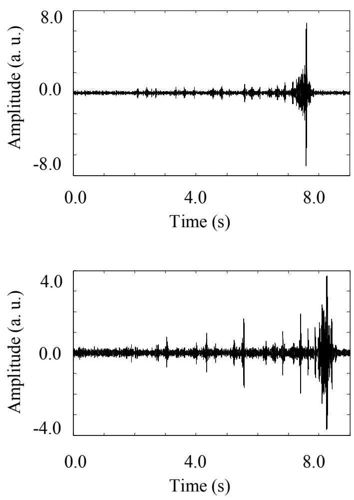


Fig. 11. Some examples of signals received at the range of 1450 km.

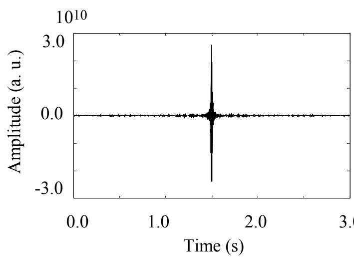


Fig. 12. Signal converged by PTR at the range of 1450 km.

4.2 Communication results

In EXP 2 and 3, due to limited ship-time, only pulse transmissions and those focusing by PTR are executed. After the pulse converged by PTR, as shown in Figs. 8 and 10, are modulated with digital data, such signals are demodulated. By this method, the performance of communication can be predicted based on the experimental data. This analysis is under the assumption that the environment is enough time-invariant and that acoustic propagation is modeled as a linear system.

After here, communication performance at the experiments are examined by such analysis, in which 1,500 symbols are modulated with binary phase shift keying (BPSK) at the data rate of 50 S/s on the pulse converged by PTR.

In Fig. 13, the demodulation results of EXP2 are shown. The demodulation results of only time reversal and our proposed method [10-17], which is combination of time reversal and one-channel decision feedback equalizer (1-DFE), are indicated as “TR” and “TR+AF”, respectively, in this figure and figures after here. The results of only using 1-DFE and multichannel equalizer are also indicated as “1-DFE” and “M-DFE”, respectively, in this figure and figures after here. In 1-DFE, the signal received at the depth of 1000 m, at the same depth as the source, is used. The results of 1-DFE are compared with ATR as a conventional method of MISO communication. In the meantime, the results of M-DFE are compared with PTR as a conventional method of MISO communication.

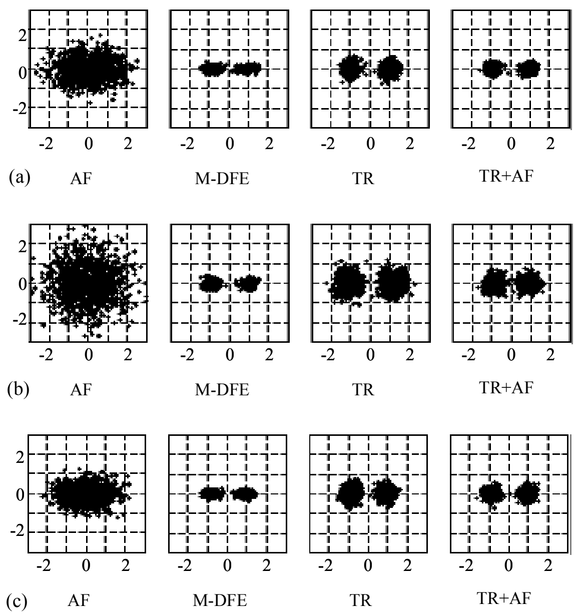


Fig. 13. Demodulation results at the ranges of (a) 20 km, (b) 30 km and (c) 40 km.

In Fig. 13, while 1-DFE cannot demodulate data at all, TR and TR+AF can achieve demodulation with no error in all cases. So, it can be said that the conventional method cannot realize communication in case of MISO communication. Thus, regarding these TR results as the predicated performance of ATR, it is expected that time reversal is superior to the conventional method in SIMO communication.

In the meantime, regarding those TR results as the performance of PTR, they are inferior to M-DFE. The reason is supposed to be the displacement and depth fluctuation due to ship movement as mentioned above. On the other hand, M-DFE can respond to change in such each channel response.

The results of EXP 3 at the range of 100 km are shown in Fig. 14. In this case, 1-DFE can also achieve communication from point to point with the conventional 1-DFE, because number of multipath signals is not so many. Then, it is expected that time reversal demonstrates its advantage at longer ranges inside SOFAR duct channel.

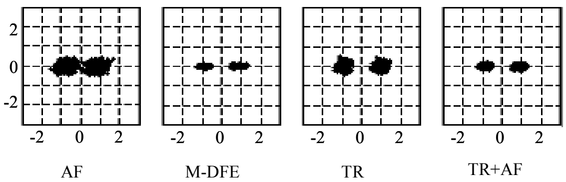


Fig. 14. Demodulation results at the range of 100 km.

In both results of EXP 2 and 3, M-DFE can be competitive to TR+AF. However, in case of M-DFE, it is necessary to adjust parameters for equalizer and the length of equalizer is much longer than in TR+AF. So in terms of computational cost, TR+AF has an advantage.

The pulse converged by PTR of the OAT experiment data are also processed similarly as EXP 2 and 3. In this case, thirty signals received at different time are processed, that is, using a kind of time diversity as mentioned above.

In Fig. 15, the results of M-DFE and TR+AF are shown. In these experiments, signals were not as affected by position fluctuation as EXP 2 and 3. Then, it is verified that time reversal is outperform conventional M-DFE.

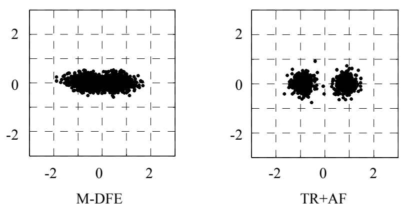


Fig. 15. Demodulation results at the range of 1450 km.

5 Communication simulation at the range over 1000 km

As mentioned above, the scenario, in which signals are transmitted several times from the base station and AUV received these signals at different time and positions while cruising horizontally at a constant speed, that is, using both of space and time diversity, has a possibility to achieve communication to AUV. Here, some of such simulation results are described in brief.

In these simulations, the water depth is 4000 m, and the sound velocity profile is a typical Munk’s profile similarly as shown in Fig. 4. Its SOFAR axis is at the depth of 1300 m and the source and receiver are placed at the same depth at the range of 1000 km. Simulations of acoustic propagation are executed by normal mode code, KRAKEN. The receiver moves horizontally assuming AUV, then, signals at 10 points are calculated at every 100 m from the point at 1000 km from the source. These signals are processed by PTR+AF and M-DFE, whose demodulation results are shown in Fig. 16. These results show that time reversal is superior to conventional M-DFE.

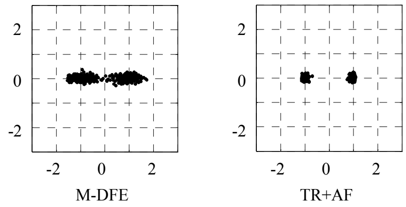


Fig. 16. Simulation results at the range of 1000 km.

6 Conclusion

The experiments of time reversal in the deep ocean at the range of up to 100 km were carried out. It was demonstrated that time reversal can converge multipath signals well and achieve communication. However, in case that each channel signal is not stable due to ship motion, the performance of time reversal is degraded and conventional DFE has an advantage.

Similarly, the analysis using the OAT experimental data and simulations at the range over 1000 km were carried out. It is clarified that time reversal outperforms conventional DFE.

Acknowledgments

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