A fundamental study on the application of passive time reversal to acoustic communication

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In JAMSTEC, an AUV named "URASHIMA" is being developed and the second of "URASHIMA" is expected to cruise to the long distance, even over 1,000 km. This research was started to make possible to achieve acoustic communication with AUV in such operation by using time reversal. We had researched on the focusing property of time reversal waves (which is equal to phase conjugate waves) and its application to the horizontal acoustic communication from an array to a point, that is, to AUV. In this paper, a fundamental study on the communication from a point to an array, that is, from AUV, using time reversal is described. The simulations of 16QAM in shallow water and the deep ocean are executed. It is revealed that by using time reversal process together with adaptive filter, it is possible to achieve higher accurate communication to long distances, because those effects does not conflict, but compensate each other. And the comparison with the conventional method is carried out.

1 Introduction

In JAMSTEC, an autonomous underwater vehicle (AUV) named "Urashima" is being developed and is undergoing technical tests of fuel cell power system[1], and it succeeded in the trial of cruising to the distance of 317 km last February. This AUV will be used in practical ocean observation in the deep sea. In the future, a second "Urashima" is expected to cruise to a long distance over 1,000 km and to be used for observation in the Arctic Ocean. In such operations, if acoustic communication with AUV is established, its operational availability will be enhanced significantly.

However, it is difficult to assure the communication channel in such an environment because many multi-path signals are mixed with the neighboring signals (intersymbol interferences : ISI) and degrade the accuracy of the communication. Conventionally, an adaptive filter is used to remove such multi-path signals. However, if many multi-path signals are received, even an adaptive filter cannot remove all of them.

Time-reversal waves can solve such problems[2-5]. Because by using time reversal, the reflected and refracted waves are converged to focus in space and time, it is expected that the signal level received at the focus increases and the symbol interferences are reduced.

We have researched the focusing property of time-reversal waves and its application for long horizontal acoustic communication, particularly in the communication from an array to a point[6-11]. Such previous studies revealed that time reversal makes it possible for the desired signal to be received at the focus, that time-reversal waves converge sharply in time and space, and that the combination of time reversal and an adaptive filter makes longer and higher-speed communication possible than the conventional method.

In this study, it is examined to use time reversal for the communication from a point to an array, which is called passive phase conjugate communication.

2 Time reversal acoustic communication

Phase conjugate waves (time reversal waves) in the ocean are generated as follows. Some acoustic waves are transmitted from a source and the signals are received at a time reversal array (TRA) as shown in Figure 1. If these signals are time-reversed and retransmitted from each element of the TRA, the signals converge to the focus point where the original source exists, and the original signal is received at the focus. Since phase conjugate waves focus to a "point" at any range by gathering the refracted and reflected waves, its focusing effect is quite different from that of the beam forming.

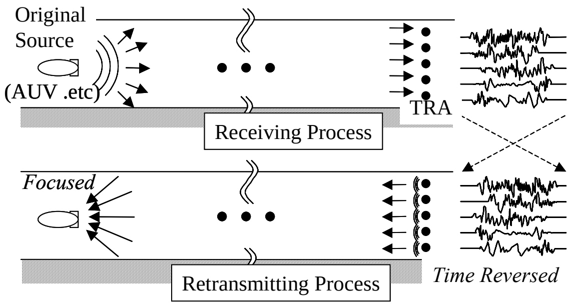


Figure 1: Schematic of phase conjugate waves in ocean

2.1 Active time reversal communication

The process of acoustic communication from an array to a point using time reversal is explained briefly as follows[9-11]. A vertical TRA is allocated and an original source (for example, an AUV) exists as shown in Figure. 1. In-phase pulses, which are passed through the roll-off filter as shown later, are transmitted from the source. These pulses are received at each element of the TRA and time-reversed. By multiplying these time-reversal pulses one by one with the symbols of the digital data sequence to be sent, time-reversal signals are composed. These time-reversal signals are retransmitted from each element of the TRA, then they converge to the focus where the original source exists. In these time-reversal signals transmitted from the TRA, time-reversal pulses are superimposed at a symbol rate, so that the signal received at the focus is the sequence of pulses without multi-path waves, that is, it is almost the same as the data sequences to be sent. In this process, time reversal signals are actually transmitted from the array, so we call it "active" time reversal communication.

2.2 Passive Phase Conjugate Communication

For the communication from a point to an array, phase conjugate (=time reversal) process can also be applied [12]. This process is explained as follows.

First, a probe pulse and a data signal are transmitted from a source as shown in Figure 2. Secondly, these signals are received at the array and the cross-correlation of these signals is calculated. Finally, the cross-correlations are summed over the channels. This process is equal to the phase conjugate, then, the multi-path waves converged and the data signal is rebuild. This method, in which phase conjugate waves are not transmitted practically, is called "virtual" time reversal or "passive" phase conjugate (PPC) communication.

However, only by this process the communication channel cannot be assured in the environment where many multi-path waves are received, as shown later. Then, in this study, the method using adaptive filter after the process of passive time reversal is proposed.

3 Communication simulation

3.1 Simulations in shallow water

Communication simulations in shallow water, as shown in Figure 3, are executed. Here, the water depth is 100 m and the distance between the source and the array is 25 km. The array is composed of seven receivers whose intervals are 15 m. The sound velocities in water and sub-bottom are 1,500 and 1,600 m/s, respectively. The pekeris solution of normal mode method, as shown in (1), is used to calculate acoustic propagation[13].

$$G_\omega(\boldsymbol{r},\boldsymbol{r}_s)=\frac{2}{H}\sqrt{\frac{2}{\pi|r-r_s|}}\sum_{n=1}^{\infty}\Big[A(k_n) \qquad (1)$$

$$\times\sin(\beta_1 z_s)\sin(\beta_2 z)\exp j\left(-k_n(r-r_s)-\frac{\pi}{4}\right)\Big],$$

$$A(k_n)\equiv\frac{1}{\sqrt{k_n}}$$

$$\times\frac{\beta_1 H}{\beta_1 H-\sin(\beta_1 H)\cos(\beta_1 H)-b^2\sin^2(\beta_1 H)\tan(\beta_1 H)},$$

$$\beta_1=\sqrt{\frac{\omega^2}{c_1^2}-k_n^2},\quad \beta_2=-j\sqrt{k_n^2-\frac{\omega^2}{c_2^2}},\quad b=\frac{\rho_1}{\rho_2},$$

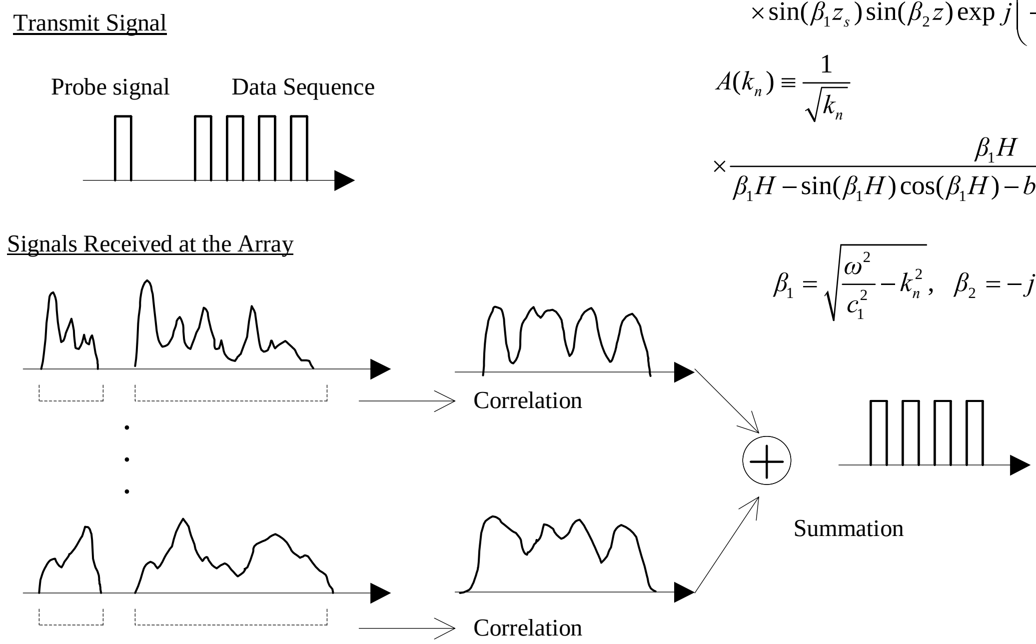


Figure 2: The diagram of passive phase conjugate communication.

where β_1, β_2 are vertical wave numbers in the sea and sea bottom respectively.

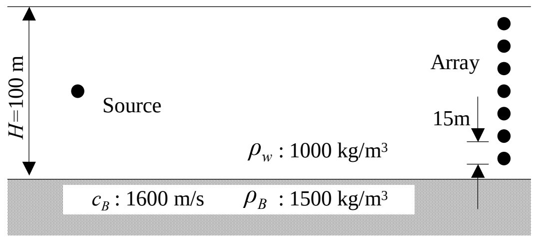


Figure 3: Simulation condition in shallow water

In communication simulations of this study, the carrier frequency is 500 Hz and the bandwidth is 150 Hz. The probe pulse is produced by being passed through the roll-off filter, as shown in Figure 4.

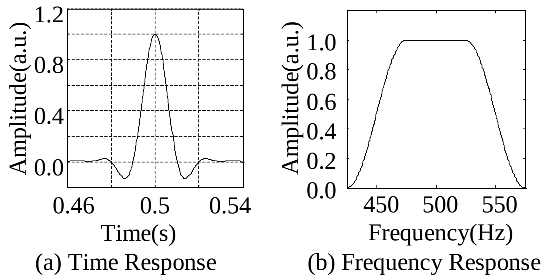


Figure 4: Roll-off filter

The simulation results when 16QAM is used as a modulation method are shown in Figure 5 and 6. In these figures, "PPC" indicates the results demodulated only by passive phase conjugate process. On the other hand, "PPC+AF" indicates the method proposed in this study, in which the signals demodulated by PPC is processed more by adaptive filter. That is the combination of PPC and adaptive filter.

In these simulations, the data signal of 1,500 symbols is transmitted. These graphs show the demodulated symbols plotted on the constellation map. In case of "PPC + AF", the training of the adaptive filter is executed. So the demodulation results from 1,000 to 1,500 symbols, after the training seems to be finished and its tap moduli are stable, are shown in these Figures. If the plotted symbols are gathered around the correct value, the communication accuracy is high. "Bit Error" indicates the number of bit errors during the demodulation of these 500 symbols. The "Output SNR" represents how close to the correct value the demodulated symbol is. In Figure 6, the demodulated symbols are plotted in time series comparing with the correct value.

As seen in Figure 5, in case of "PPC", the demodulation is not completed, that is, the conventional method using only passive phase conjugate cannot assure the communication channel. On the other hand, in case of "PPC + AF", bit error seldom happens and the received symbols are demodulated almost perfectly. That is, the combination of passive phase conjugate and adaptive filter makes it possible to assure the communication channel in the condition where the method using only passive phase conjugate does not.

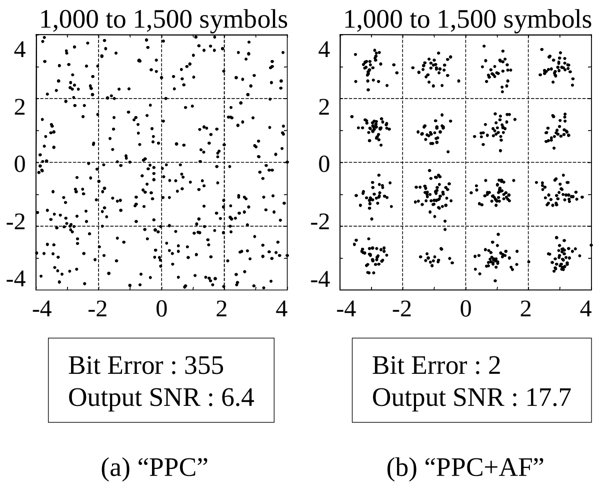


Figure 5: Demodulated results on the constellation map

This is because signals, which do not converge, appear like "noise" and disturb the demodulation for the next symbol in case of "PPC". In the meantime, in case of "PPC + AF", adaptive filter removes such signal like "noise", then, the demodulation accuracy is higher.

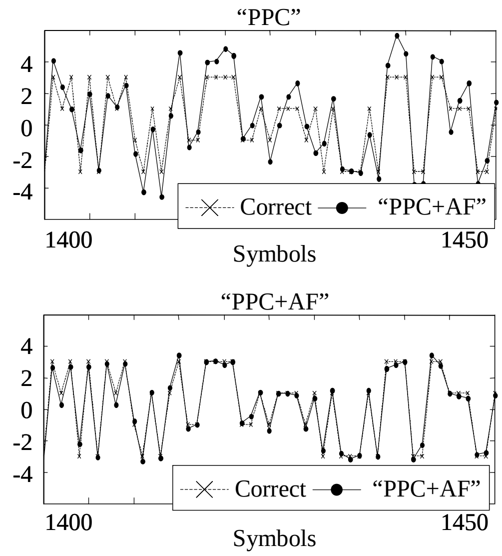


Figure 6: Demodulated symbols in time series

In Figure 6, such effect is also found since the demodulated symbols in case of "PPC + AF" are closer to the correct symbols than in case of "PPC".

3.2 Simulations in deep ocean

In this section, the simulation results in the deep ocean are described. The sound velocity profiles of the simulation environment are shown in Figure 7. The parabolic equation (PE) method is used to calculate acoustic propagation[14], in which the depth and range samplings are 0.5 and 1.0 m, respectively. The carrier frequency, the bandwidth and the roll-off filter are the same as in the previous section.

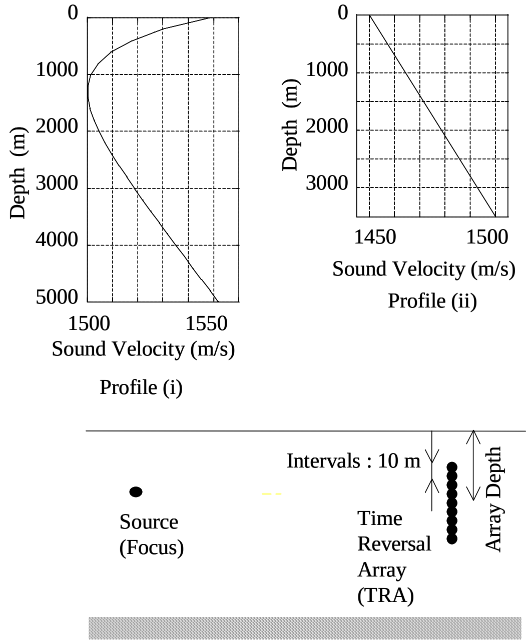


Figure 7: Simulation condition in the deep ocean

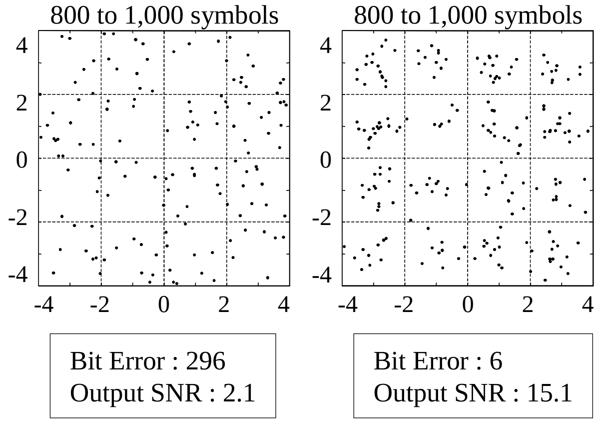
In case of Profile (i), the range is 500 km and the depth is 5,000 m. The source is at the depth of 2,000 m and the center of array is at 4,000 m. The array is composed of 19 receivers, whose interval is 10 m. The simulation result in this profile is shown in Figure. 8.

In case of Profile (ii), the range is 1,000 km and the source depth is 2,000 m. The center of array is also at the depth of 2,000 m. The results are shown in Figure 9.

These results reveal that by using passive phase conjugate and adaptive filter together makes possible the acoustic communication under environment where it is impossible by using only passive phase conjugate, even in such deep ocean. In particular, it is significant that it is possible with the array whose length is shorter than the water depth.

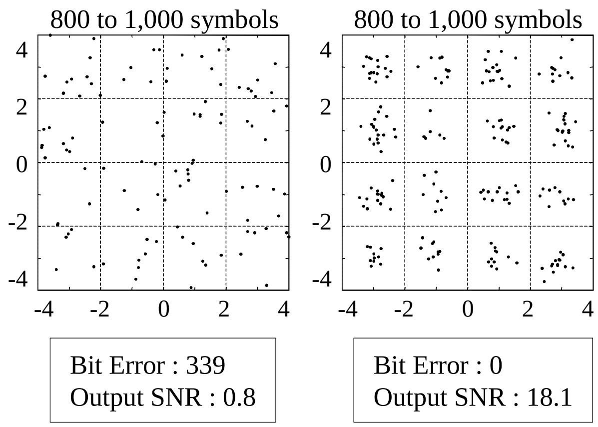
4 Summary

The basic research on passive phase conjugate (=time reversal) communication is carried out. It is clarified that there is a possibility to communicate to the long distances at high data transmission speed by combining passive phase conjugate and adaptive filter. Hereafter, tank experiments and sea trials will be executed, and the study on the effects of variant disturbance such as Doppler or surface waves will be performed.



(a) “PPC” (b) “PPC+AF”

Figure 8: Simulation results in case of Profile (i)



(a) “PPC” (b) “PPC+AF”

Figure 9: Simulation results in case of Profile (ii)

Acknowledgement

This work was partially supported by a 2004 Grant-in-Aid for Young Scientists (A) (Grant No. 16686050) from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

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