

## Demonstration of time-reversal communication combined with spread spectrum at the range of 900 km in deep ocean

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### 1. Introduction

Within the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), a project to develop a new autonomous underwater vehicle (AUV) is being planned. It will have the capability to cruise long distances of over several hundred kilometers. Achieving acoustic communication with such a long-range AUV, even at a low data transmission rate, will be important.

We have investigated time-reversal communication for such a long range. Through time reversal, multipath waves converge to a focus in time and space [1,2]. Thus, the intersymbol interference (ISI) decreases. In our previous studies, a method of combining time reversal and adaptive equalization was proposed [3–7]. At-sea experiments have been carried out to confirm the effectiveness of such time-reversal communication. In our first experiment at a range of 10 km, it was demonstrated that time-reversal communication could be accomplished in the deep ocean [8]. Our subsequent experiments were executed at various ranges of up to 300 km in the outer ocean [9,10].

Our latest experiment was executed at ranges from 500 to 900 km for passive time-reversal communication. For the ranges of 500 and 600 km, the results demonstrate that communication can be satisfactorily achieved with the method of combining time reversal with adaptive equalization.

However, at the range of 900 km, it was impossible to achieve communication, owing to the low signal-to-noise ratio (SNR) using the existing projector. However, communication was realized by combining spread spectrum (SS) techniques [11–14]. With such a method, it became possible to extend the communication distance at the expense of the data rate. In this paper, the results of these experiments are described.

### 2. Experimental procedure

The experiment was carried out in an area of relatively flat bathymetry near the Izu-Ogasawara islands. The bathymetry profile is shown in Fig. 1. In the measurements at ranges of

700 and 900 km, the source was installed at points Tx1 and Tx2, respectively, and the receiver array was installed at point Rx. The source depth was 1,000 m, which is the depth rating of the projector. The receiver array was moored at the depth around the axis of the channel duct. The sound velocity profiles at these points are also shown in Fig. 1.

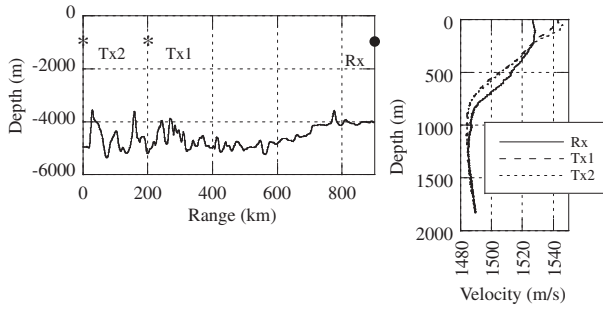
A projector (EAI-PS-500D) was used as a sound source with a center frequency of 500 Hz, bandwidth of 100 Hz, and source level of 186 dB re 1  $\mu$ Pa at 1 m. The receiver array was composed of 20 receiver systems, which were spaced approximately 6.0 m apart. The total length of the array was approximately 114 m. HTI-90-U hydrophones were used as the receivers.

In this experiment, only passive time-reversal communication was performed, because the results can be interpreted as the predicted performance of active time reversal, to some extent, as well as passive time reversal itself.

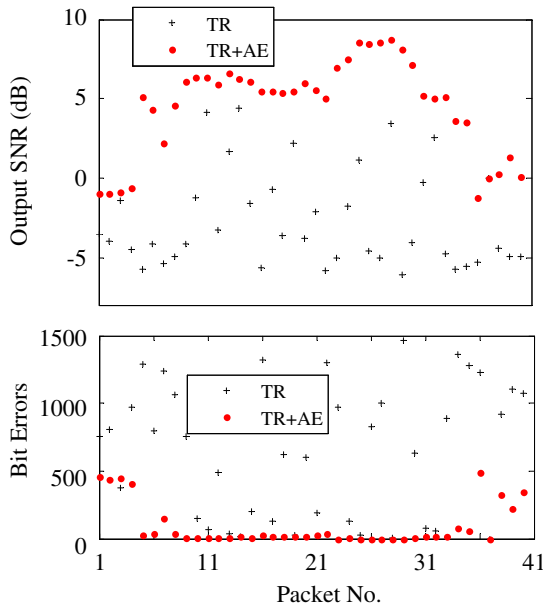
As a probe signal for passive time reversal, the M-sequence signal was used to improve the SNR of the probe signal similarly to in our previous experiment [10]. After being received at the array, the probe signal is correlated with the original M-sequence, and then correlated with the received data signal as the passive time-reversal process.

In addition to the above process, in the experiment at the range of 900 km, the SS technique was introduced to extend the communication distance under the limitation of the source level of the projector. In this case, each symbol in the data signal is spread with a seven-chip Barker code. That is, the effective data rate is decreased to one-seventh. The probe signal is the same as in the case of not using the SS technique. The received probe signal is first correlated with the original M-sequence signal, and then correlated with the received data signal as passive time reversal. After that, the signal is correlated (despread) with the original Barker code signal. By this method, the demodulated signal level is increased, in addition to the time-reversal effect, by the correlation gain of the Barker code at the expense of data rate. Similarly to the cases of not using the SS technique, this signal is further processed by an adaptive equalizer.

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**Fig. 1** Bathymetry (the upper panel) and sound velocity profiles (the middle and lower panels).



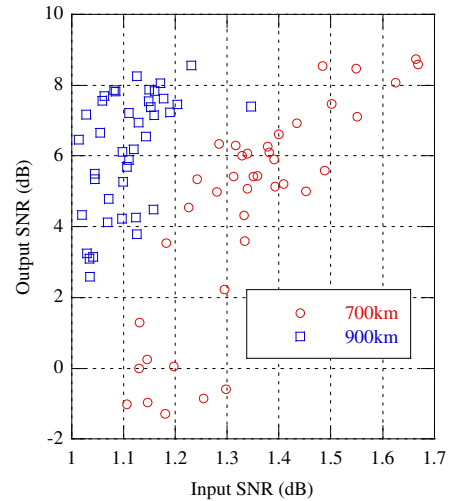
**Fig. 2** Output SNR and bit errors in the experiments at the range of 700 km.

### 3. Experiment results

#### 3.1. Results at range of 700 km

In the measurement at the range of 700 km, 511-symbol M-sequence signals were transmitted as the probe signal. The data signals contained 1,785 symbols. One packet was composed of the probe signal and the data signal. Forty packets were transmitted every 2 min in this measurement. As the modulation method, binary phase shift keying (BPSK) was adopted, and the symbol rate was 100 bps. Thus, one bit expresses one symbol.

In Fig. 2, the demodulation results are shown. The upper and lower graphs are for the output SNR and bit errors, respectively, during the forty-packet transmission. In these figures, “TR” indicates the case when only time reversal is used, and “TR+AE” indicates the method in which time reversal and adaptive equalization were combined. In the case of TR+AE, the initial 200 symbols are used to train the adaptive equalizer. In the middle of the forty transmissions, the TR+AE method managed to accomplish demodulation. However, in the beginning and at the end of the transmissions, demodulation failed.



**Fig. 3** Output SNR against SNR of the received signal at ranges of 700 and 900 km.

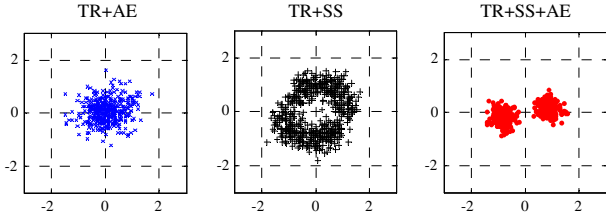
In Fig. 3, the output SNR is plotted against the SNR of the received signals in the case of TR+AE. In this figure, the results at the range of 900 km, which are described in the next subsection, are also shown. Note that the signals used in calculating the SNR include multipath signals. This graph shows that the performance is affected mainly by the SNR of received signals, and that small changes in the SNR govern the success or failure of demodulation. From these results, it was judged that 700 km is the maximum distance at which communication could be accomplished with the current projector source level.

Note that the occurrence of a few errors during 1,585 symbols can be acceptable. In our present plan, approximately 400- or 500-bit signals, including the AUV status and observation data, will be transmitted in one packet. Thus, there is a threefold redundancy. Additionally, such a small number of errors can be compensated with error correction codes.

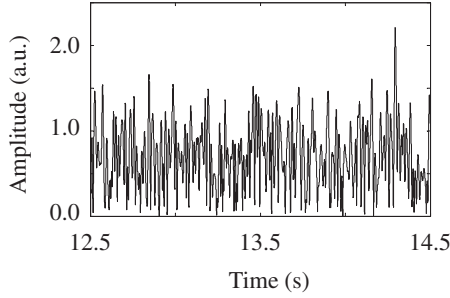
#### 3.2. Results at range of 900 km

In the measurements for the 900 km range, it was impossible to realize communication by sending the same signals as used at the 700 km range. Thus, as mentioned above, the SS technique was introduced to extend the communication distance. In this measurement, the data signal was composed of each symbol modulated (spread) with a seven-chip Barker code. Thus, the effective data rate was decreased to 100/7 bps. The probe signal was the same as the one used for the 700 km range.

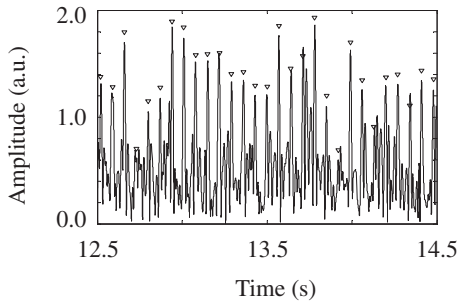
As explained above, the received probe signal is correlated with the original M-sequence signal, and subsequently correlated with the received data signal as passive time reversal. Next, this signal is correlated (despread) with the original Barker code signal. Thus, data symbols can be obtained at intervals of 0.07 s with the ISI almost eliminated. The obtained results at this stage are indicated as “TR+SS.” These signals are additionally processed with adaptive equalization. The results after this process are indicated as “TR+SS+AE.”



**Fig. 4** Demodulation results of packet No. 2 at the range of 900 km.



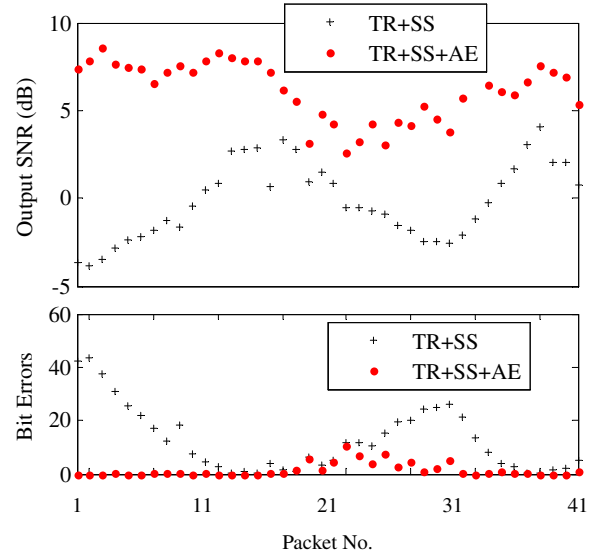
**Fig. 5** Signal after passive time reversal at the range of 900 km.



**Fig. 6** Signal after TR+SS process at the range of 900 km.

In Fig. 4, some demodulated results are shown for the cases of TR+SS and TR+SS+AE, together with TR+AE for comparison. As mentioned above, it is not possible to realize demodulation by TR+AE. In the case of TR+SS, the phase is rotated. In the case of TR+SS+AE, such phase rotation is compensated and demodulation with no error can be achieved. In Figs. 5 and 6, the absolute envelopes after only passive time reversal and after the TR+SS process are shown, respectively. Comparing Figs. 5 and 6, it is seen that peaks at the symbol rate, which are indicated by upside-down triangles, appear after the Barker code correlation. Nevertheless, the residual sidelobes remain. They are eliminated with adaptive equalization in TR+SS+AE; then, demodulation is achieved.

In Fig. 7, the output SNR and bit errors are shown during the forty-packet transmission every 2 min. In the results of TR+SS around packets No. 1 to 9 and around No. 26 to 34, a similar phase rotation to that shown in Fig. 4 is observed. In the case of TR+SS+AE, such a phase rotation is compensated well. In the results around No. 19 to 24, where the noise level increased, bit errors occurred even in case of



**Fig. 7** Output SNR and bit errors in the experiments at the range of 900 km.

TR+SS+AE. These results indicate that the method of TR+SS+AE works well, except for the results around No. 16 to 26. These results show that by introducing the SS technique, it is possible to achieve communication over longer ranges at the expense of the data rate. As seen in Fig. 3, output SNR is improved even at low input SNR compared with the results at the range of 700 km.

As mentioned above, the data rate in the case of using SS is one-seventh that in the case of not using SS. Thus, bit errors in Fig. 7 are desired less than those of the results in Fig. 2.

#### 4. Conclusions

At-sea experiments on passive time-reversal communication in the deep ocean at ranges of up to 900 km were conducted. Demodulation was achieved up to ranges of 700 km by the method of combining time reversal and adaptive equalization. At the range of 900 km, the method of combining time reversal, SS, and adaptive equalization enabled communication at the expense of data rate subject to the limited source level of the projector. In future work, quantitative research summarizing this and previous experimental results will be conducted.

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