Acoustics'08 Paris
June 29-July 4, 2008
www.acoustics08-paris.org

Passive phase conjugation processing to forward scattering waves by target in shallow water

Yoshiaki Tsurugaya[a], Toshiaki Kikuchi[b] and Koichi Mizutani[c]

[a]NEC@Corp., 1-10@Nissin-cho, Fuchu, 183-8501 Tokyo, Japan
[b]National Defence Academy, 39-21 Uhoyabe 4-chome, Yokosuka, 238-0024 Kanagawa, Japan
[c]Tsukuba Univ., Tsukuba Science City, 305-8573 Ibaraki, Japan
y-tsurugaya@bp.jp.nec.com

This paper describes a detection of an underwater target using a passive phase conjugation processing. It is assumed that a sound source and an array are disposed in shallow water, and a target exists between them. A traveling wave from the sound source and a scattered wave from the target are received at the array. However, they are received almost simultaneously. In addition, because a level of the traveling wave is considerably larger than that of the scattered wave, the detection of the scattered wave is difficult. Then, the traveling wave components are removed from signals received at the array. And, a passive phase conjugation processing is executed to the signal. The result shows that it has the position information of a target. This relation is used as a matched-field method to detect a target.

1 Introduction

The researches on time reversal increase it in the field of underwater acoustics [1-9]. When searching for an object in shallow water, the detection of the object often becomes difficult for the reflection on the surface and at the bottom of the sea. The research that processes a phase conjugation to reflected waves from an object attract attention recently [10-14]. These researches use backscattered waves from objects. However, an enough scattered wave might not be obtained for a small object and the sound wave of a low frequency. On the other hand, the level of a forward scattering wave is larger in general for the small object than the level of the backscattered wave. However, the traveling wave from the sound source besides the forward scattering wave is present in an area in a distance from the object, too. We previously separated scattered waves from the mixture wave that consisted of the traveling wave and the scattered wave [15]. Here, a passive phase conjugation is processed to the scattered wave separated like this. In addition, the relation between the result of a passive phase conjugation processing and the sound field is clarified, and a matched-field method is constructed. In section 2, a time reversal and a passive phase conjugation are outlined. In section 3, the simulation result is shown.

2 Phase Conjugation in Shallow Water

2.1 Phase conjugation

A sound source and an array are set up in shallow water as shown in Fig. 1. The sound waves transmitted from the sound source are received at the array allocated from it to a remote point. And, when transmitting from the array again after a phase conjugation processing is executed to the signal, the sound waves at a reception point are shown by the following equation [1],

$$G_{cw}(\mathbf{r},\mathbf{r}_s)=\sum_{n=1}^{N}G_{\omega}^{*}(\mathbf{r}_n,\mathbf{r}_s)G_{\omega}(\mathbf{r},\mathbf{r}_n)\quad , \qquad (1)$$

where $G_{\omega}(\mathbf{r}_n,\mathbf{r}_s)$ is Green's function concerning propagation from a sound source to an element of a transducer array and $G_{\omega}(\mathbf{r},\mathbf{r}_n)$ is Green's function concerning propagation from the element to a reception point. $\mathbf{r}$ shows the range, and s, n, and $*$ show the sound source, element number, and complex conjugate, respectively. It is shown in a time domain by the following equation though Eq. (1) is a presentation form in a frequency domain [2],

$$P_{pc}(r,z;t)=\sum_{j=1}^{J}\int G_{\omega}(r,z,z_j)G_{\omega}^{*}(R;z_j,z_{ps}) \times e^{i\omega T}S^{*}(\omega)e^{-i\omega t}d\omega\,, \qquad (2)$$

where G_{ω}, t and z are Green's functions, time, and depth, respectively. R is a horizontal distance from a sound source to an array, and r is a range from an array to a reception point. $S(\omega)$ is frequency spectrum of the sound wave transmitted from the sound source, and ω is an angular frequency. The range of an application of this equation is not specially limited to a sound source though this equation is often used when a convergence property near the sound source of the phase-conjugate wave is examined.

2.2 Sound fields except sound source

The relational expressions shown in the previous section are not the equation limited to the sound source. Then, a phase conjugation to sound field at arbitrary points other than the source location is examined. That is, an arbitrary point is assumed in the middle of a sound source and an array as shown in Fig. 1. The arbitrary point is considered to be a position of a new sound source. A driving signal of the

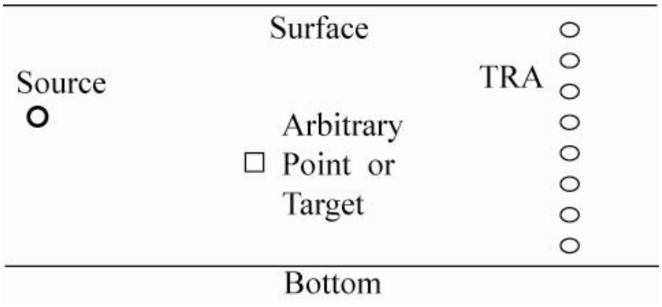


Fig. 1. Geometry of a source, an array and a target

new sound source is supplied from the original sound source. Therefore, a relation between the frequency spectrum of the original sound source and the frequency spectrum of the new sound source is expressed as follows,

$$S_R(\omega) = S(\omega) G_\omega(r_R; z_R, z_{ps}) \ , \qquad (3)$$

where suffix p means arbitrary point.

Next, a phase conjugation at arbitrary point is examined by using Eq. (2) and Eq. (3). In case of a conventional phase-conjugate wave, a sound pulse transmitted from the sound source is received with the transducer array for the disposition shown in Fig. 1 and a time reversal processing is executed at each element. Afterwards, when the signals are transmitted again from each element, the similar pulse to the transmitted pulse is formed at the source location. Then, it is examined whether the characteristics similar to a conventional phase-conjugate wave is maintained at an arbitrary point. That is, the similarity with a direct wave and a time-reversed signal is examined at the arbitrary point on the middle of the sound source and transducer array.

2.3 Passive phase conjugation

A sound source and a receiving array are allocated in shallow water. When a probe signal p_i and a data signal p_d are transmitted from the sound source, and a sound wave is received with m th element of the receiving array (position $\mathbf{r}_m$), a cross-correlation function of those signals is expressed by the following equation [16],

$$R_{id}(\mathbf{r}_m; t) = \int_0^T p_d(\mathbf{r}_m; t'+t) p_i(\mathbf{r}_m; t') dt' \ . \ (4)$$

Next, the cross-correlation function of all elements is added.

$$S(t) = \sum_{m=1}^{M} w_m R_{id}(\mathbf{r}_m; t) \qquad (5)$$

It is known that the S(t) becomes a phase conjugation of the probe signal. This technique is called a passive phase conjugation.

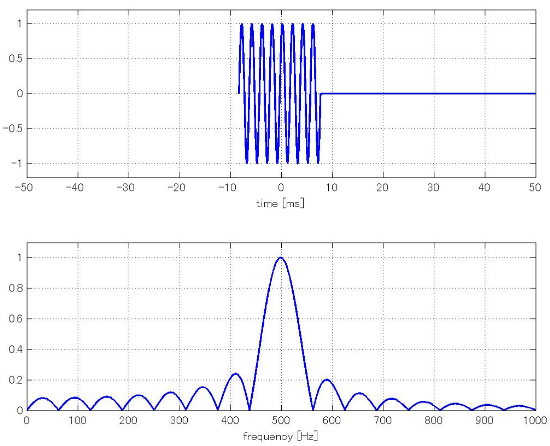


Fig. 2. Pulse and spectrum used for simulation

3 Simulated results

3.1 Comparison between direct wave and time reversal wave at arbitrary point

The depth is set to 100 m in the disposition shown in Fig. 1 and the range between the sound source and the transducer array is set to 2.5 km. The sound speed and the density of seawater are 1500 m/s and 1000 kg/m^3, respectively. Those of sediment are 1600 m/s and 1500 kg/m^3, respectively. A tone burst wave of a centre frequency 500 Hz and a pulse width 8 cycles is transmitted from the sound source set up in 50 m in depth. The wave form and spectrum of the tone burst wave are shown in Fig.2. A wide band pulse is used in the simulation to investigate the waveform of the pulse in detail. These sound pulses are received at the transducer array, and the time reversal processing is executed at each element. And, the time-reversed signals are re-emitted from each element. The re-emitted sound waves are received at the waypoint of the sound source and the transducer array (at the arbitrary point in Fig. 1). And, a similarity of the phase conjugated signal and the driving signal formed there is examined.

At a point of the range 1 km from the sound source, the sound wave that enters directly from the sound source is compared with the time reversal wave. In this case, the pulse transmitted from the original sound source is a tone burst wave. The spectrum shown in Fig. 2 corresponds to $S(\omega)$ of Eq. (2). The band width of the frequency spectrum used to calculate is wide-band 350 Hz because it expresses the waveform at an arbitrary point in detail. This bandwidth corresponds to the band width to the third lobe of the frequency spectrum that shows in Fig.2. On the other hand, the frequency spectrum of the new sound source is easily obtained by the Fourier transform of the sound pulse that enters directly from the original sound source at the position of the new sound source though the frequency spectrum of the new sound source is related to the frequency spectrum of the original sound source by Eq. (3). A position of the new sound source is set to the range 1 km and 50 m in depth. The sound pulse that enters from the original sound source at the position of the new sound source and the waveform of the time reversal wave are shown in Fig. 3. The upper figure is the sound pulse that enters from the original sound source to the position of the new sound source, and the bottom figure is the waveform of the time reversal wave.

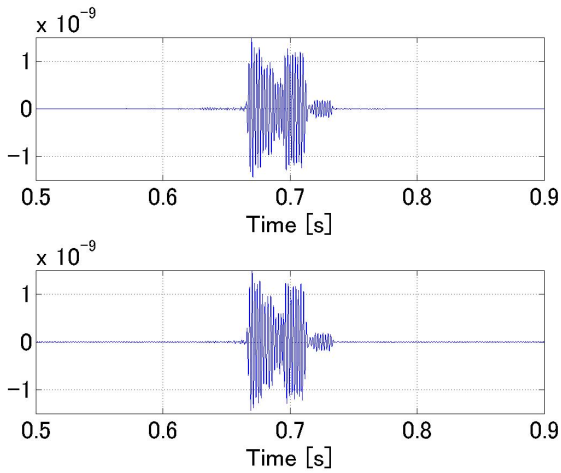


Fig. 3. Comparison between direct wave and time reversal wave at middle point.

Because the travelling direction of the time reversal wave is opposite to the travelling direction of the direct wave, the time reversal wave is displayed by the reversing time coordinate. Moreover, the frequency spectrum $S_p(\omega)$ shown in Eq. (2) is obtained from the sound source directly by its Fourier transform considering the sound wave that enters at a reception point to be a new sound source.
The waveform of the sound wave that enters directly from the sound source agrees with the waveform of the time reversal wave. It is understood from the above-mentioned result that the phase conjugation is maintained at the arbitrary point between the source and the array.

3.2 PPC of wave travelling from source

A sound source and a transducer array are allocated in shallow water as shown in Fig. 1. The range from the sound source to the array is 3 km. A target is allocated to the range 1.5 km and 50 m in depth. The material of the target is iron, and both the height and width are 2 m in the size. A tone burst wave of a centre frequency 500 Hz and a pulsewidth 8 cycles is transmitted from the sound source, and a pulse is transmitted from the sound source located at depth 50 m. The sound pulse transmitted from the sound source hits the target and scattered waves are generated. Therefore, a traveling wave from the sound source and scattered waves reach the receiving array almost simultaneously. A passive phase conjugation is applied to signals received at the array. Hereafter, the result that the passive phase conjugation is processed is called PPC. That is, a correlation processing is performed to the signal received at each element of the array according to Eq. (4). In this case, a probe signal and a data signal are the same. The correlation obtained in each element of the array is added according to Eq. (5). Fig. 4 shows the result that the PPC is processed. The effect of the scattered wave by the target is not observed though the waveform agrees with the autocorrelation waveform of the transmission pulse shown in Fig. 2.

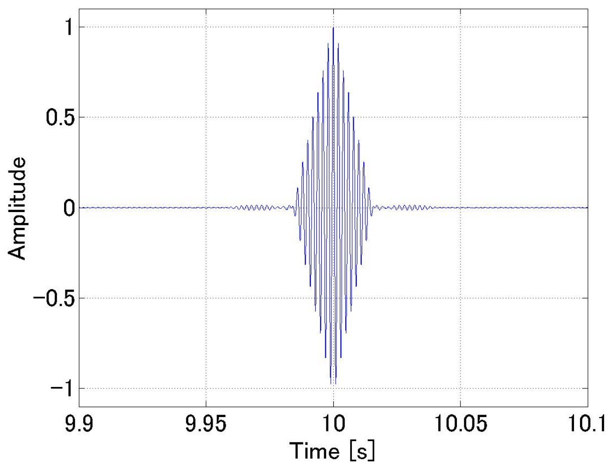


Fig. 4. The PPC to the mixture wave with traveling wave and scattered wave.

In general, because a level of a traveling wave is larger than a level of a scattered wave, it is difficult to detect the scattered wave. Then, a sound wave is transmitted when a target is not present beforehand, and the signal received by each element of the transducer array is preserved. Afterwards, a sound wave is transmitted when a target is present, and a traveling wave and a scattered wave are received by each element of the transducer array.

3.3 PPC for wave scattered from target

A signal that receives when the target is not present from the signal that receives when the target is present is subtracted. The passive phase conjugation (PPC) described in the previous section is applied to the subtracted signal.
A target is allocated to the range 1.5 km and 50 m in depth, and a pulse is transmitted from the sound source located in 50 m in depth. And, after the component of the traveling wave is removed from the signals received at the array, the PPC processing is executed. The result of processed PPC is shown in Fig. 5. It is a symmetric waveform that centers on ten seconds that are the repetition rates of the pulse.

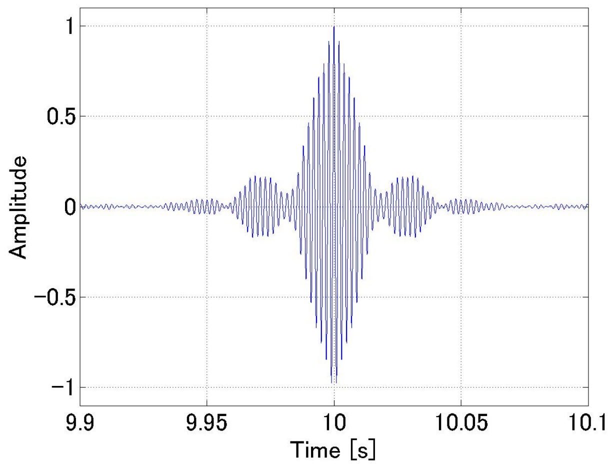


Fig. 5. The PPC for wave scattered from target

It is necessary to confirm it though the PPC obtained thus is the PPC only of the scattered wave from the target. To confirm that the obtained PPC is the PPC only of the scattered wave, the position of the target is assumed to be a new source location. Naturally, a pulse transmitted from the new source location is not a tone burst wave. A driving pulse is the pulse that enters from an original sound source to the new source location.

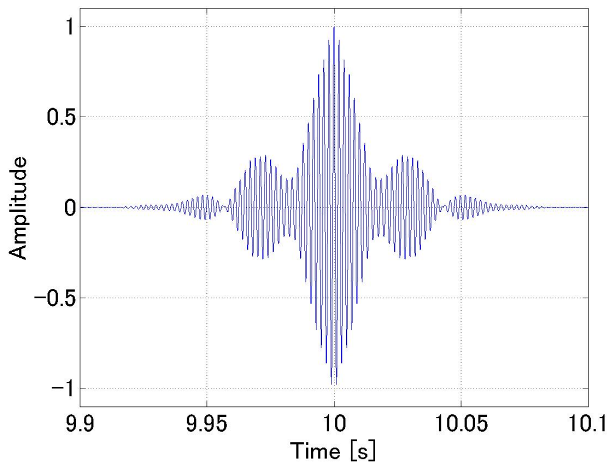
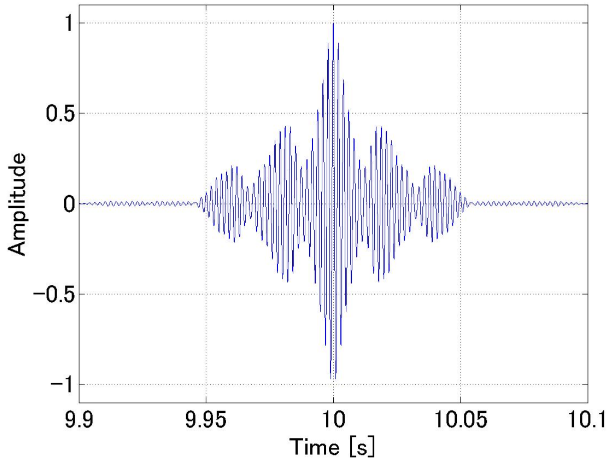


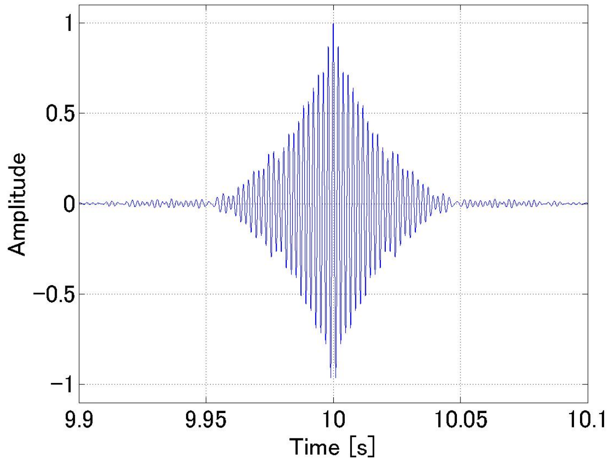
Fig. 6. The PPC for a input pulse at middle point

A pulse is transmitted from the new source location, and the PPC processing is executed to the received signal.

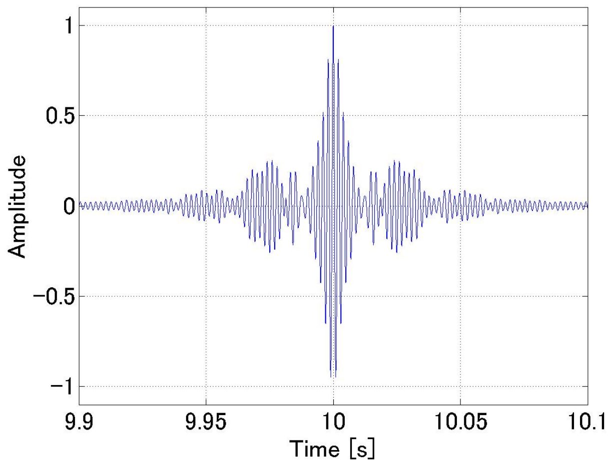
Fig.6 shows the result that the passive phase conjugation is processed to the signals. The obtained PPC (Fig. 6) agrees with the PPC (Fig. 5) of the above-mentioned scattered wave well. It is clarified that the component of the traveling wave is removed as a result, and only the scattered wave from the target is displayed.



a)



b)



c)

Fig. 7. The PPC for targets with different range
Range a) ; 1.3 km, b); 1.6 km, c); 1.7 km
Depth 50 m.

3.4 Relation between target position and PPC

In this section, a relation between a position and the PPC for a target is investigated. The propagation environment is similar to the case in the foregoing paragraph. The position of the target only is changed and the PPC to the scattered wave of the target is obtained. Fig. 7 is the PPC as the parameter as for the range of the target. The range of the target is 1.3, 1.6, and 1.7 km. On the other hand, the depth of the target is all 50 m. It is clear to change the PPC greatly depending on the range of the target. Similarly, when the depth of the target is changed, the PPC is greatly changed.

Fig. 8 shows the PPC for the target on the range 1.5 km and 20 m in depth That is, it is thought that the position and the PPC of the target are in implications

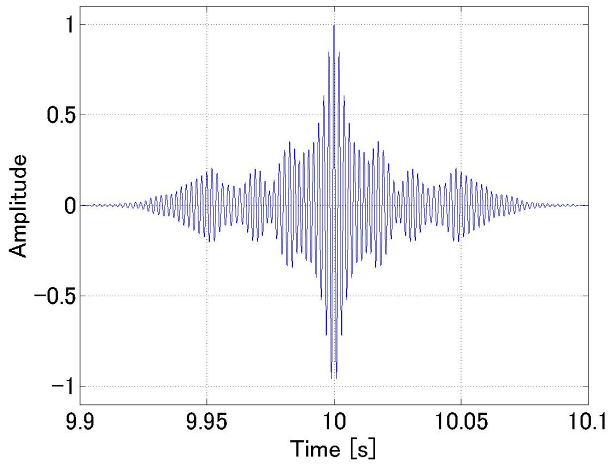


Fig. 8. The PPC for target at range 1.5 km, depth 20 m.

3.5 Correlation and PPC

The PPC of scattered waves from a target is straightforward related to the pulse that enters at the position of the target. Therefore, the PPC of the scattered wave of the target is similar with the correlation

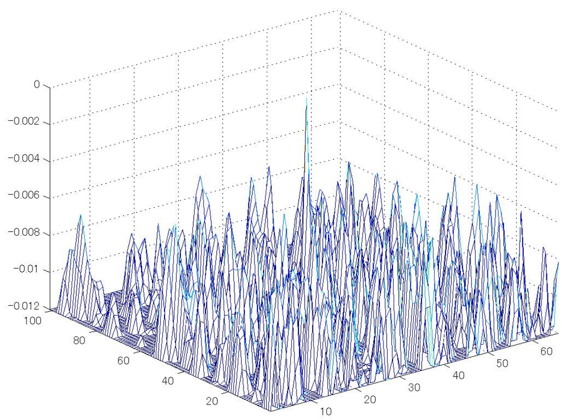


Fig. 9. The correlation of the PPC for target and the autocorrelation of the pulse that enters at sound field.

waveform of the pulse that enters at the position of the target. On the other hand, the pulse that enters at the arbitrary point in a sound field is uniquely decided by the propagation environment. That is, the PPC of the scattered wave of the target has information for the position of the target. This relation is used as a matched-field method to detect a target. The autocorrelation of the pulse that enters at an arbitrary point and the correlation with the PPC are shown in Fig. 9 for the target put in the range 1.5 km and 50 m in depth. In this figure, the position of the target appears clearly.

5 Summary

A method of detecting a target using the PPC for the forward scattering wave from a target in shallow water was proposed. First, a phase conjugation at an arbitrary point that did not contain a position of sound source was investigated. That is, the waveform of the pulse that enters from the sound source to the arbitrary point and the time-reversed pulse is similar.
Next, a traveling wave from the sound source was removed, and a passive phase conjugation processing was added only to the scattered wave from the target. That is, the PPC of the scattered wave from the target agreed with the auto-correlation function of the pulse that entered to the position of the target for a small target compared with the wavelength.
A matched-field method was constructed by applying this relation. The pulse that enters into the sound field plays an important role in this method. On the other hand, a lot of researches are performed for a long time as for the acoustic wave propagation in shallow water. Therefore, the sound field at the sound field, that is, target position can be easily presumed.

References

[1] D. R. Jackson and D. avid R. Dowling, "Phase conjugation in underwater acoustics", J. Acoust. Soc. Am. 89, 171-181 (1991)

[2] W. A. Kuperman, W. S. Hodgkiss, and H. C. Song, "Phase conjugation in the ocean: Experimental demonstration of an acoustic time-reversal mirrora," J. Acoust. Soc. Am. 103, 25-40 (1998)

[3] H. C. Song, W. A. Kuperman, and W. S. Hodgkiss, "A time-reversal mirror with variable range focusing," J. Acoust. Soc. Am. 103, 3234-3240 (1998)

[4] W. S. Hodgkiss, H. C. Song, W. A. Kuperman, T. Akal, C. Ferla , and D. R. Jackson "A long-range and variable focus phase-conjugation experiment in shallow water," J. Acoust. Soc. Am. 105, 1597-1604 (1999)

[5] J. S. Kim, H. C. Song, and W. A. Kuperman, "Adaptive time-reversal mirror," J. Acoust. Soc. Am. 109, 1817-1825 (2001)

[6] J. S. Kim, W. S. Hodgkiss, W. A. Kuperman, and H. C. Song, "Null-broadening in a waveguide," J. Acoust. Soc. Am. 112, 189-197 (2002)

[7] S. Kim, W. A. Kuperman, W. S. Hodgkiss, H. C. Song, G. F. Edelmann, and T. Akal,, "Robust time reversal focusing in the ocean," J. Acoust. Soc. Am. 114. 145-157 (2003)

[8] S. C. Walker,_P. Roux, and W. A. Kuperman, "Focal depth shifting of a time reversal mirror in a range-independent waveguide," J. Acoust. Soc. Am. 118, 1341-1347 (2005)

[9] S. C. Walker, W. A. Kuperman, and P. Roux "Active waveguide Green's function estimation with application to time-reversal focusing without a probe source in a range-independent waveguide, " J. Acoust. Soc. Am. 120, 2755-2763 (2006)

[10] G. Montaldo, M. Tanter, and M. Fink, "Revisiting iterative time reversal processing: Application to detection of multiple targets " J. Acoust. Soc. Am. 115, 776-784 (2004)

[11] C. Prada, S. Manneville, D. Spoliansky, and M. Fink, "Decomposition of the time reversal operator: Detection and selective focusing on two scatterers," J. Acoust. Soc. Am. 99, 2067-2076 (1996)

[12] N. Mordant, C. Prada, and M. Fink, "Highly resolved detection and selective focusing in a waveguide using the D.O.R.T. method," J. Acoust. Soc. Am. 105, 2634-2642 (1999)

[13] D. H. Chambers, "Analysis of the time-reversal operator for scatterers of finite size," J. Acoust. Soc. Am. 112, 411-419 (2002)

[14] D. H. Chambers, A. K. Gautesen, "Time reversal for a single spherical scatterer," J. Acoust. Soc. Am. 109, 2616-2624 (2001)

[15] Y. Tsurugaya, T. Kikuchi, K. Mizutani, "Target scattering waves emitted from TRA in shallow water," J. Acoust. Soc. Am. 122, 3023 (2007)

[16] D. Rouseff et al., IEEE, J. Oceanic Eng. 26, 821 (2001)