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Multistatic Time Reversal

Hisashi Shiba

Radio Application Division, NEC Corporation, 1-10, Nisshin-Cho, Fuchu, Tokyo, Japan

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ABSTRACT

In the multi-path sonar application, time reversal methods are noticed to be effective for target detections. The time reversal methods possess an advantage that they dose not require propagation route structure in advance. However, the methods are hard to indicate target distances in the highly noisy or highly reverberant conditions because it is difficult to distinguish signal peaks from noise or reverberations. If the methods estimate target direction, it is able to obtain target position by multiple sonars even in such conditions. Target positions are estimated by detecting a crossing point of target direction lines which are results of multiple sonar time reversal processing and drawn form each sonar. This new concept is presented and problems for practical use are discussed in this paper.

INTRODUCTION

The time reversal processing attracts attention as a new paradigm for various regions of acoustics and radios these days as a sort of inverse problem solutions. It is motivated by the fact that the wave function has time reversal invariance, and dose not require a transfer function. Although the realistic ocean environment is not stationary and the dissipation has to be taken into account, several reseraches have been certified its validity.

One of the most active research domains is the medical applications [1]-[6]. Human body is a complex material with an inhomogeneous ultrasonic refraction distribution and an appropriate sample to verify the effectiveness of the time reversal techniques. The non-destructive inspection is also promising area [10]. Although most time reversal researches use acoustics, some tirals are focusing on electromagnetic wave applications [5]-[9]. The time reversal methods are proven to be effective for various usages especially in the multi-path environment like applying sonars in shallow water. Recent researches report that the time reversal processing show huge potentials in the underwater communications [19]-[26], [32]. And more, a unique application is found in the water front protections by an acoustical barrier [18].

The time reversal methods' remarkable feature is a self focusing [11]-[13]. This feature is enhanced by iterations [14], [15] and brings improvement of the signal to noise or reverberation ratio [16], [17]. In particular, some recent researches are noteworthy because they enable acoustical focal point controls which are very useful for target identification if its scanning time is tolerable [27]-[30]. Some of them propose unique technique searching under the sediment for mine detections by shifting the focal point just above the sediment [31]. The focal point control is also serviceable for high efficiecy underwater communications by aiming the focus at its companion station.

In majority time reversal target detection researches, sonars are arranged for forward scattering or sub-forward scattering detections regarding target strength patterns. Since it is hard to hold targets between sonars for optimal forward scattering in practical operations and a large system are required to install with a transmitter and receiver separately, a back scattering configuration with a small system which serve as a transmitter and receiver is considered as a starting point of our research.

The time reversal methods are proven to be effective for target detections. However, the methods are hard to indicate target distances in the highly noisy or highly reverberation conditions because it is difficult to pick up just signal peaks from noise or reverberation dominant sounds. It seems that this problem has not been so scrutinezed so far. At first, this distance problem is explained in detail in this paper.

If the methods estimate target direction, it is able to obtain target position by multiple sonars even in such severe conditions. Target positions are estimated by a crossing point of target direction lines which are results of each sonar time reversal processing. This new and simple approach is introduced after the time reversal limitation explanation. Then, without being satisfied with this approach, an additional extension is proposed. The extension receives signals from other sonars for signal enhancements like multistatic sonars. This is more robust than traditional time reversals in the low S/N or low S/R conditions by integrating other sonar signals. The detection coverage is also discussed with signal timings. The time variation is a common problem in the time reversals, and it needs further investigations for practical operations.

TIME REVERSAL TARGET DETECTION AND ITS LIMITATION

The time reversal methods possess a decisive advantage that they dose not require medium refraction structure along its propagation route in advance. Although the methods suppress noise and reverberations, they cannot indicate target distances in the highly noisy or highly reverberant environments even in the completely stationary medium, because it is difficult to distinguish signal peaks from noise or reverberations in such conditions. The target distances are usually estimated by the signal peak timing of the initial not time reversed sound. The time reversed signal peak indicates only the target existence and its timing does not provide the target distance. This problem is not sufficiently realised, hence it should be explained more carefully.

The time reversal target detection by single sonar is divided into the following 4 steps. 1) Transmit sounds by the sonar. 2) Receive reflected sounds from the target. 3) Time reverse and retransmit the received signal. 4) Re-receive the reflected sounds. All steps are drawn in Figure 1. The time reversal processing is not iterated in this speculation, because the iteration requires commensurate time and it tends to focus one target. Some researces are reverable for multible targets, but they need more iterations [12], [13].

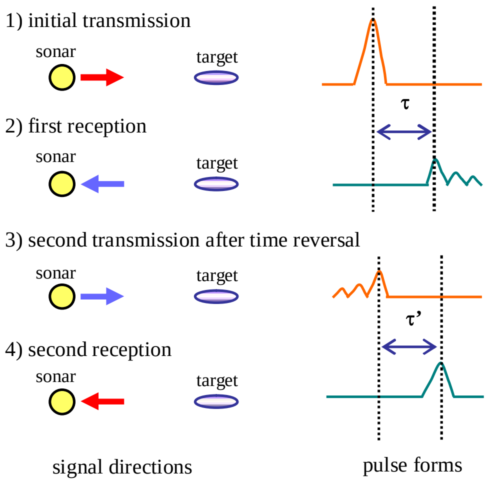


Figure 1. Time reversal signal forms and peak tim-

At the first step a steep pulse is emitted. The next step is the first reception of an echo by the target. The echo is followed by a reverberation trail because of the multi-path environment. The signal peak is the direct reflection by the target, and it is easily distinguishable form noise and reverberations. Then received echo is time reversed and transmitted. The time reversal signal period is usually defined based on the neccesary searching area size. Each element of the sonar just transmits the time reversed signal and it is not required to transmit with directional beams at this step. Finally the time reversed echo is received. The pulse form is very clear at this final step and shows a similar shape if the sonar array is suffitinetly large to rebuild original wave form and the environment is ideally stationary with negligible dissipation. The diversed sounds are collected by the time reversal at this fourth step.

As a matter of fact, the fourth step signal peak timing depends on the time reversed peoriod length at the third step. If the start timing of the time reversed transmittion and the signal peak timing are different in the time reversed sound at the third step, the signal peak timing based on the time reversal transmission start timing doesn't indicate the target distance. The time reversed signal peak should be considered as the basis of the target distance estimation using the second reception. The interval between the time reversed signal peak at the third step and re-received signal peak at the fourth step show equal timing of the initial received signal peak at the second step which is not time reversed. That means τ' is equal to τ in Figure 1.

On the contrary, in the case of highly noisy or highly reberverant conditions as in Figure 2, the target distance is not able to be identified because it is difficult to find out the target echo. Although several peaks are found at the second step as in Figure 2, there is no significant feature caused by the direct target scattering. In some feasible conditions a sharp peak may be found at the fourth step, but the peak position does not tell us the true target distance. This characteristic that the time reversal target detection cannot display target distances with severe noise or reberverations means the method may not applicable for practical ASW usages. Though this problem does not essentially occur with focal point controlling time reversal systems, since the focus position is under control, the focal point scanning needs a progessive acceleration.

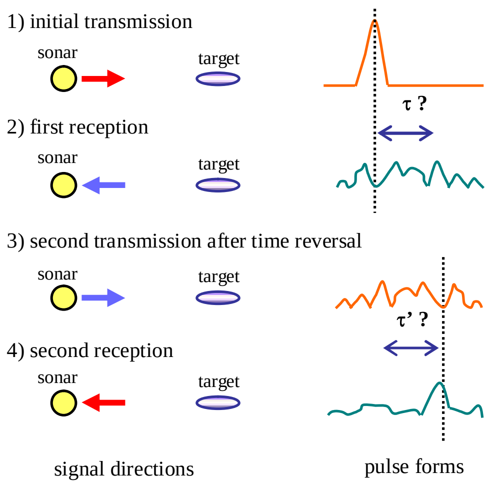


Figure 2. Time reversal signals in highy noisy or highly revebrent cases.

This distance problem is not limited in the backscattering configurations. Any configurations including the forward scattering are not able to derive target distances in the highly noisy and reverberant conditions. Figure 3 is an example which has an initial transmitter (sonar A) and a time reversal transmitter (sonar B) separately. In the severely noisy cases, the sonar B can not catch targets. After the time reversal transmittion by sonar B, the sonar A obtains a higher possibility of target detections.

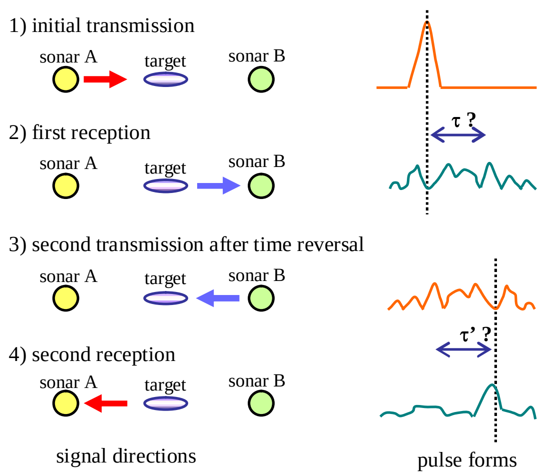


Figure 3. Time reversal signals in a forward scattering configuration.

TARGET POSIOTION IDENTIFICATION BY MULTIPLE TIME REVERSAL SONARS

Instead of the distance resolution, the time reversal methods are able to provide the target directions, if the sonars show directionally variable response with an array configuration. The target direction accuracy is enhanced by signal integration along each direction. If multiple time reversal sonars are employed, target positions are able to be derived from the multiple target directions even if each distance accuracy is extremely low. Target positions are estimated by detecting a crossing point of target direction lines which are results of multiple sonar time reversal processing and drawn from each sonar. Suppose the sonar A detect a target direction without its distance like in Figure 4 (a). Then if the second direction is indicated by the sonar B, the target position is identified by the crossing point as in Figure 4 (b).

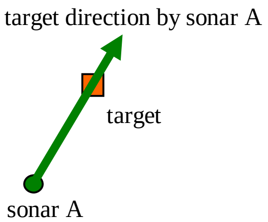


Figure 4 (a). Target direction by a single sonar

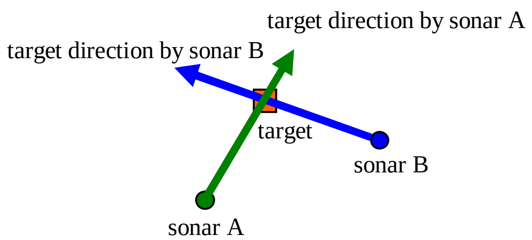


Figure 4 (b). Target position by two sonars

Realistically target directions are finite and each sonar confines a target within a fan shaped area. Therefore the target position is described by a polygonal probability area as a result of overpapping of multiple target direction fan areas like Figure 5. If the beam directional and distance resolutions are described by a single peak distribution for instance a Gaussian, the target existence probability in the polygon becomes a sort of distorted Gaussian as a result of probability multiplications. Sonar arrangement is important because the target position accuracies depend on its and sonar positions, considering that the polygon sizes and shapes vary depending on relative locations of targets and sonars.

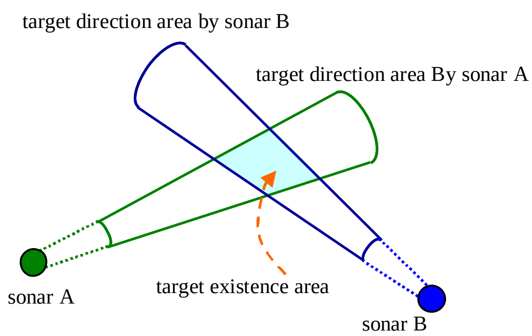


Figure 5. Target existance polygonal area

In the case of only the horizontal direction is concerned, three or more sonars are required on the sea surface and they should not be arranged on one line as in Figure 6, since it is impossible to estimate the target position if the target is on the same line with all sonars. The Figure 6 shows an example of two sonars (A and B) and the target on the same line by a top view. The target position is not defined by these two sonars. Adding the third sonar C clarifies the target position. It is plausible to arrange sonars on the equal interval lattice like a triangular grid considering a symmetrical detection probability.

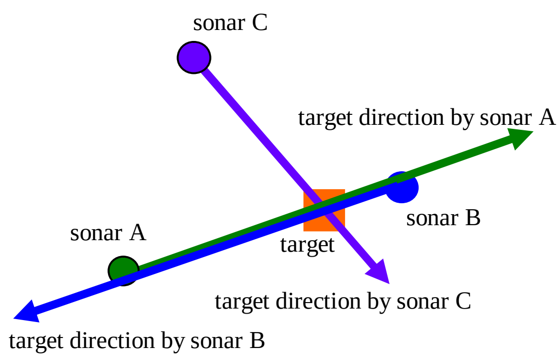


Figure 6. Target position identification by three sonars

Sonar signals should be emitted by different timing or the signal should be modulated sonar by sonar, such as different frequencies or different codes, for avoiding interferences.

MULTISTATIC TIME REVERSAL CONFIGURATION

The above method implies that each sonar receives signals transmitted by itself. And the signals are time reversed independently sonar by sonar. That individual processing is simple and useful, however, as a next step the method is able to be extended to receiving signals from other sonars for signal enhancements. Integrating the time reversed sounds from other receiver sites strength the signal to noise or reverberation ratio. This procedure seems like multistatic sonar systems, so, this extension should be called 'multistatic time reversal'. The new method is different from the traditional multistatic sonar at the point of the time reversal as explained below.

It is very easy to understand the multistatic time reversal processing by two sonar configuration as in Figure 7. In this figure, the initial not time reversed signals are drawn by solid lines, and the time reversed signals are drawn by dashed lines. Relatively weak signals are drawn by thinner lines. The new method characteristic becomes clear by tracing the sound from one sonar (sonar 1 in Figure 7). The sonar 1 transmits at the first step. The sonar 1 and 2 receive the echo from the target at the second step. Next, each sonar reverses the signal by time and retransmits. Both sonars receive the echo of the time reversed signal from the target at the final step. If the time reversed sound ideally reconstructs the initial wave form, the sonar 2 receives no signal at the fourth step because the sonar 2 transmits no signal at the first step. However, the sonar 2 receives signals to some extent at the fourth step realistically, because of the imcompleteness of the time reversed wave caused by the imcomplete coverage of the initial echo, the sound dissipations and the environmental time variation. Considering the echo from the target at the second step as an initial transmission of the target, the target receives the rebuilt wave by the sonar 2's time reversal at the third step. Then the target retransmits the time reversed sound to the sonar 2. If the wave form transmitted by the target is time symmetric, the retransmitted wave form is equal to the initial target transmittion. Therefore, the sonar 2 receves the signal affected by the mult-path environment as same as the initial target transmission. That is, the sound power tends to be weak even if the wave form is not time symmetric. On the other hand, sonar 1 receives the waves rebuild by both sonar time reversals. The sonar 1 receives completely reconstructed but time reversed signal, if the time reversal condition is impeccable

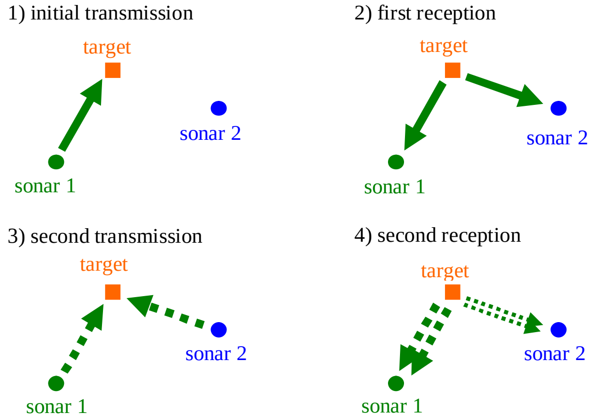


Figure 7. Tracing of sonar 1 sound in the multistatic configuration

Tracing sounds by both sonars completes the multistatic time reversal idea. Both sonars receve sounds transmitted by their companions with their own transmission as in Fiugre 8. In this figure the signals originated from sonar 1 are drawn in-green, and the signals from sonar 2 are drawn in blue. The both sonars may consequently receive the obstructive residual signals by their companions. The residual signals are able to be eliminated by filtering techniques such as frequency filterings.

The multistatic time reversal easily allows any number of transmitters depending on the situation. Moreover, transmitting sites are flexibly assigned and changeable for every transmission. For effective operation of multstatic time reversal sonars, transmission timings and wave forms should be carefully considered for planning a detection coverage area and suppressing interference among sonars. Frequency or code modulation is preferable rather than waiting other sonars' transmissions for quick target detections.

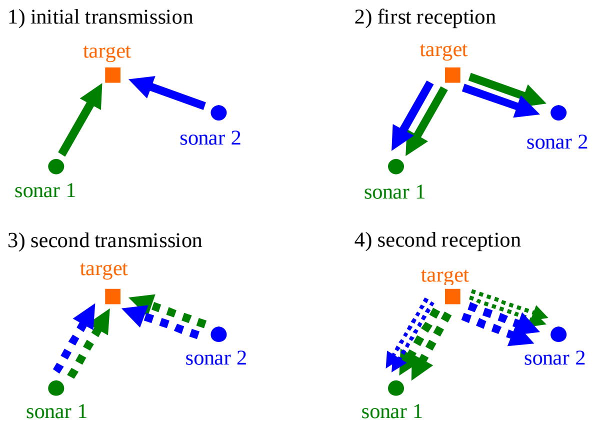
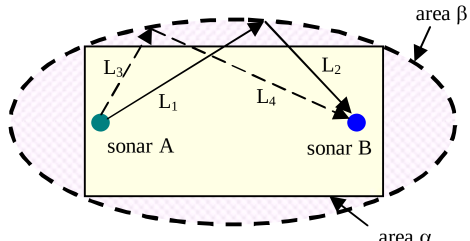


Figure 8. Tracing of sonar 1 and 2 sound in the multistatic configuration

The initial transmission timing is not restricted by the other site sonars, if the sonar signals are distinguishable sonar by sonar. But the time reversal timing is limited by the receiving timing. It should not be allowed to reverse signals during the receipt from the other sonars. One of the simplest time reversal timing is waiting appropriate signals from all sonars. This approach is tightly connected with the expecting detection coverage. It is not usally predictable when the appropriate signals arrive. If the sonar coverage is defined in advance, the latest target echo arrival is predictable.

TARGET DETECTION COVERAGE

It is plausible to define the target detection coverage as an ellipse determined by the sonar locations like conventional multistatic sonar coverages. This ellipse has to circumscribe the desired area planned by operation staff in advance. For instace, if the desired area is α as in Figure 9, the circumscribing ellipse is indicated as the area β. The ellipse parameter 'L' is decided based on the sonar sweeping period.

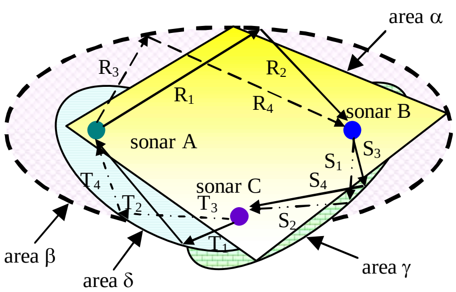


$L_1+L_2=L_3+L_4=L$

Figure 9. Detection coverage area.

A three sonar example is drawn in Figure 10. The coverage is a compound of three elliptical areas β, γ and δ. This compond area has to circumscribe the desired area α. The elliptical parameters R, S and T are defined by the transmission timing. It seems hard to estimate the optimized transmission timings. The transmission timing is important for reducing the waiting intervals, considering the multistatic time reversal processing tends to consume much time.

For preserving the coverage, the multistatic time reversal needs about twice time comparing with usual procedures. However, it is noticeable that the formar part of the time reversal process is a usual multistatic technique. If the operation time is shortly restricted, this method is able to show its intermediate result as a usual multistatic.



$R_1+R_2=R_3+R_4=R$
$S_1+S_2=S_3+S_4=S$
$T_1+T_2=T_3+T_4=T$

Figure 10. Detection coverage area by three sonars.

PROBLEMS TO SOLVE FOR PRACTICAL USE

The multistatic time reversal must be useful, however, there remains some problems for further considerations. First of all, the stability against time varying environment has to be evaluated more thoroughly. The time varying componets are sonars, targets, sea surface, and sea water. The problem of the former two componets is their position variations. Moving targets have to be considered for the usual ASW operations. Although some sonars like dipping sonars and sonobuoys are fixed point obserbations, they usually suffer oceanic fluctuations. If the position variarion is negligibley smaller than the sound wavelength during the time reversal, it has no problem. Suppose that the target distance is ~10km, and then the operation time needed for the multistatic time reversal is about 30sec. If the sound frequency is ~1.5kHz, the acceptable movement during the operation for negligibility is sufficiently less than 1.0m. This is not unfeasible demand for the sonar fluctuation restrictions, but it is too small for moving targets. Since this is the estimation for ideal conditions and the condition is not essential, further theoretical investigation is required for the real efficency estimation. Some recent researches which compensate position variations [32] suggest that there is room for further study.

The latter two problems have to take into account the oceanic features. It is reasonable to assume that the water medium is stable during the above mentioned operating period. On the other hand, the sea surface is not able to be considered as constant, because surface waves contain wavelengths comparable to the sonar sound depending on the transmitted frequency. But the oceanic fluctuations may not be severe problem from many succesfull time reversal experiments [28]. Though the evaluated frequency for time variations is lower than usual ASW sonars, lower frequencies are able to become acceptable if they exceed the traditional sonar performance. This time variation problem is a fundamental issue which is common in the time reversal schemes, and it also needs further researches.

SUMMARY

A new extension of the time reversal was proposed as multistatic time reversal. The method holds the same features as usual time reversal methods. Time reversal methods aggregate signals scattered in time. The time scattering is a result of the space scattering. In other words, the multi-path propagation converts the space scattering to the time scattering, and the time reversal method inversely converts the time scattering to the space scattering. This leads us to the view point that a larger array is virtually generated by reflectors and scatterers in the ocean through time reversals.

In addition to that, the multistatic time reversal method aggregates signals scattered not only in time but in space. Hence the multstatic is a multiplication of virtual array and an expansion of the aperture. If the signals are integrated sufficient period by adequate number sonars, the time reversals reproduce the original wave form if dissipation like absorption by the oceanic medium is negligible. It will be one of the most influential tools for multi-path investigation in a variety of fields in the near future. As a further pursuit, time variation impacts have to be examined for the practical environments which are not considered to be stationary.

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