Passive reverberation nulling for target enhancement

H. C. Song, a W. S. Hodgkiss, W. A. Kuperman, K. G. Sabra, and T. Akal
Marine Physical Laboratory, Scripps Institution of Oceanography, La Jolla, California 92031-0238, USA
M. Stevenson
NATO Undersea Research Centre, La Spezia, Italy

(Received 19 December 2006; revised 29 May 2007; accepted 25 September 2007)

Echo-to-reverberation enhancement previously has been demonstrated using time reversal focusing when knowledge of the channel response between a target and the source array elements is available. In the absence of this knowledge, direct focusing is not possible. However, active reverberation nulling still is feasible given observations of reverberation from conventional source array transmissions. For a given range of interest, the response between the source array elements and the dominant sources of boundary reverberation is provided by the corresponding reverberation from this range. Thus, an active transmission can be projected from the source array which minimizes the energy interacting with the boundaries at a given range while still ensonifying the waveguide between the boundaries. As an alternative, here a passive reverberation nulling concept is proposed. In a similar fashion, the observed reverberation defines the response between the source array elements and the dominant sources of boundary reverberation at each range and this is used to drive a range-dependent sequence of projection operators. When these projection operators subsequently are applied to the received data vectors, reverberation can be diminished. The improvement in target detectability is demonstrated using experimental data with an echo repeater simulating the presence of a target. © 2007 Acoustical Society of America.

PACS number(s): 43.30.Gv, 43.30.Hw [DRD]

Pages: 3296–3303

I. INTRODUCTION

Reverberation from rough ocean boundaries often limits the performance of active sonar systems in shallow water environments. Recently, a time reversal (TR) approach for reverberation mitigation has been investigated in theory and subsequently demonstrated experimentally to reduce prominent reverberation returns by retransmission from a time reversal mirror (TRM). The basic idea is that a time-gated portion of reverberation provides the transfer function between the TRM and the sea surface/bottom boundaries for a given range cell, which can be exploited either for focusing back to the corresponding interface or reverberation nulling. The motivation behind reverberation nulling is to minimize the acoustic energy incident on the boundaries in a specific range cell while still projecting energy into the water column for the ensonification of targets.

Reverberation nulling occurs naturally with the TR method when focusing acoustic energy on a target due to shadowing of the boundaries below and above the focus in a waveguide (see Fig. 2(b) in Ref. 6). Indeed, Kim et al. demonstrated the potential of echo-to-reverberation enhancement using the TR approach over a simple broadside (BS) transmission. First, with a probe source (PS) at 4.7 km range from the TRM in 110-m-deep water, the increased level of ensonification at the PS and the decreased level of reverberation at the TRM were measured separately and combined to estimate the monostatic echo-to-reverberation enhancement. Second, improved target echo-to-reverberation enhancement was confirmed bistatically using an artificial target of unknown target strength (TS) located next to the PS. Here, “monostatic” and “bistatic” refer to the use of a receiving array collocated with or separated from the source array. In Sec. III, we will show the results of a monostatic echo-to-reverberation enhancement experiment as opposed to our earlier bistatic demonstration.

Although TR focusing is a useful demonstration of waveguide physics, it is unlikely that the target actually will be in the immediate vicinity of a PS. In this case, it is not possible to focus directly on the target. If a priori knowledge of target range is available, however, focusing on a target still is feasible using an iterative time reversal approach without a PS by iteratively retransmitting a selected portion of data which contains the target echo.

Instead of boosting the target echo by TR focusing, we also can achieve echo-to-reverberation enhancement by actively reducing the reverberation given observations of reverberation from conventional source array transmissions. In this paper, the terms “active” and “passive” refer to the TRM: “active” when a TRM attempts to focus on a target or null out reverberation by transmitting an environmentally dependent excitation vector signal while “passive” when a TRM simply transmits conventional BS signals followed by processing of the returned time series. For a given range of interest, the response between the source array elements and the dominant sources of boundary reverberation is provided by the corresponding reverberation from this range. Thus, an active transmission can be projected from the source array which minimizes the energy interacting with the boundaries.

---
aAuthor to whom correspondence should be addressed. Electronic mail: hcsong@mpl.ucsd.edu
at a given range while still ensonifying the waveguide between the boundaries. While active reverberation nulling also has been demonstrated experimentally, the range over which boundary interaction is suppressed is limited and thus different excitation vectors must be transmitted for each range unless the specific range of a target is known.

As an alternative, we consider a passive reverberation nulling concept which operates only on the returning reverberation from conventional source array transmissions without a PS and a priori knowledge of target range. In a similar fashion, the observed reverberation defines the response between the source array elements and the dominant sources of boundary reverberation at each range. A collection of target-free responses can be used to drive a range-dependent sequence of projection operators based on the eigendecomposition of the data covariance matrix. When these projection operators subsequently are applied to the received data in the presence of a target, reduction of reverberation results in enhancing the target echo. This approach essentially is equivalent to the eigenvector-based projection method in radar where strong interferences are spatially is equivalent to the eigenvector-based projection operators subsequently are applied to the received data in the presence of a target, reduction of reverberation while Cox exploited Doppler and applied an squares algorithm to reject high-frequency under-ice reverberation, bottom reverberation.2 While active reverberation nulling from conventional source array transmissions without a PS and a priori knowledge of target range. In a similar fashion, the observed reverberation defines the response between the source array elements and the dominant sources of boundary reverberation at each range. A collection of target-free responses can be used to drive a range-dependent sequence of projection operators based on the eigendecomposition of the data covariance matrix.9,10 When these projection operators subsequently are applied to the received data in the presence of a target, reduction of reverberation results in enhancing the target echo. This approach essentially is equivalent to the eigenvector-based projection method in radar10–13 where strong interferences are suppressed by projecting the array data onto the subspace that is orthogonal to the interference subspace. In reverberation-limited active sonar conditions, reverberation can be treated as a strong interference although it represents a collection of distributed sources at the interface rather than a single point source. Despite the analogy, we are not aware of any previous work reported in the literature applying the projection approach to low or mid-frequency reverberation nulling. Hodgkiss and Alexandrou proposed an adaptive least-squares algorithm to reject high-frequency under-ice reverberation, while Cox exploited Doppler and applied an adaptive beamforming algorithm with a towed horizontal array to detect a weak moving target in the presence of strong bottom reverberation.

This paper is organized as follows. Section II describes the reverberation experiment conducted during FAF-04. Section III demonstrates monostatic echo-to-reverberation enhancement of the TR approach using an echo repeater simulating a target. Finally, Sec. IV demonstrates improved target detectability resulting from the passive reverberation nulling approach.

II. REVERBERATION EXPERIMENT

A time reversal experiment (FAF-04) was conducted jointly with the NATO Undersea Research Center in July 2004 both north and south of Elba Island, off the west coast of Italy. The reverberation experiment reported in this paper was carried out in a flat region of 120-m-deep water north of Elba on July 22 (JD204). The source-receive array (SRA or TRM) consists of 29 transducers spanning a 78 m aperture (2,786 m interelement spacing from 32 to 110 m) as shown in Fig. 1. The maximum source level of each element was 178 dB re 1 μPa. An echo repeater (ER) simulating a target was deployed at 70 m depth which was drifting along with the R/V Alliance. The target strength (TS) of the ER was set to 30 dB. A sound speed profile collected during the experiment is displayed in Fig. 2 featuring an extended thermocline down to 70 m depth. We confine our interest to narrowband continuous wave (cw) pulses as in our previous papers,2,3,6

III. ECHO-TO-REVERBERATION ENHANCEMENT

In this section, monostatic echo-to-reverberation enhancement is demonstrated using the echo repeater shown in Fig. 1. First, consider a conventional BS transmission as a base line.

The SRA simply transmits a 100 ms cw pulse at 3500 Hz on all elements simultaneously and that BS transmission is captured by the ER. Next, the SRA repeats the BS transmission while the ER transmits the previously captured signal simultaneously with an appropriate time delay simulating a target echo. Immediately after the BS transmission,
the SRA starts recording the monostatic reverberation return which contains the target echo as well. An example of the measured monostatic reverberation field at the SRA plus ER transmission is shown in Fig. 3(a) when the ER was about 3 km away from the SRA. Note that three of the SRA transducers (Channels 7, 22 and 25 from the bottom) were disabled during the experiment indicated in thick blue horizontal lines in Figs. 3(a) and 3(b).

Next, consider the case of TR implementing active focusing. A 100 ms cw pulse at 3500 Hz is transmitted initially from the ER (acting as a PS), and is received and time reversed by the SRA. The time-reversed signal from the SRA then is refocused on and captured by the ER. As in the BS transmission, the SRA repeats the TR transmission while the ER transmits the captured signal with an appropriate time delay. The monostatic reverberation field plus ER transmission recorded by the SRA is shown in Fig. 3(b). The presence of a target around 3.7 s corresponding to the ER range of 3 km is indicated clearly as opposed to Fig. 3(a) where the target echo is hardly visible. Note that the dynamic range of Fig. 3(a) is 5 dB higher than that of Fig. 3(b) due to the difference in the transmitted level. In other words, approximately 5 dB less energy is transmitted by the SRA for the TR transmission compared to the conventional BS transmission as previously observed in Ref. 6.

Finally, Fig. 3(c) shows a comparison between the BS and TR transmissions. The levels are obtained by incoherent averaging of the 26 active channels. The TR level (red) has been increased by 5 dB to compensate for the lower level transmission by the SRA. The echo-to-reverberation enhancement is about 7–8 dB over the BS transmission in addition to an overall reverberation reduction of 5 dB. This result is consistent with the one reported in Ref. 6 where the increased ensonification level at the target (5 dB) and the decreased reverberation level (3 dB) were measured separately without using an echo repeater.

IV. PASSIVE REVERBERATION NULLING

Although the active TR focusing approach shows a significant echo-to-reverberation enhancement, it is assumed that the channel response from a target is known to the SRA by using a probe source in the vicinity of the target. If a priori knowledge of target range is available, either active reverberation nulling or an iterative time reversal approach still can be employed to enhance the target echo as described in Sec. I. In this section, we consider the more typical situation where neither a PS nor a priori knowledge of target range is available. Here we propose a passive reverberation nulling approach to improve target detection from BS transmissions containing a target echo as shown in Fig. 3(a). The approach essentially is equivalent to the orthogonal projection methods found in adaptive beamforming algorithms where strong interferers are suppressed.

During the FAF-04 reverberation experiment described in Sec. II, a 100 ms cw BS transmission was carried out every 15 s over approximately 4 min (JD204 11:20:15-11:23:45) while the ER at 3 km range retransmitted the captured echo every other BS transmission (i.e., 30 s). As a result, a total of 16 BS reverberation returns were collected, half of which included the target echo as well. Without any signal processing, the incoherent reverberation levels are shown in the upper left and right panels of Fig. 4: (a) reverberation alone and (b) echo plus reverberation. Interestingly, the target at around 3.9 s happens to occur very close to the strong reverberation return around 4.1 s, making it difficult to determine the presence of the target in Fig. 4(b). We also
will show results of target detection from echo plus reverberation returns later in Sec. IV B. Note that this portion of the experiment was carried out half an hour earlier than the monostatic echo-to-reverberation data collection reported in Sec. III where the ER is at around 3.7 s. The BS transmission loss \( H_20849 \) from the SRA is displayed in Fig. 5 a indicating that the reverberation return mainly is due to interaction with the sea floor in a downward refracting environment [see Fig. 2]. Here we do not attempt to reproduce the experimental results shown in Fig. 4(a) [or Fig. 5(b)] except to capture the general features of reverberation from a propagation perspective.

A. Projection operator

The basic idea behind reverberation nulling is based on the observation that in the absence of a target \( s \), a time-windowed segment of reverberation data transformed into the frequency domain \( x \) can be represented as

\[
x = h + n,
\]

where \( h \) the transfer function vector between a TRM array and the corresponding sea surface and/or bottom boundaries for that range cell. Note that \( h \) incorporates the reverberation scattering strength as well as the source level as a scale factor. The additive white noise \( n \) is assumed uncorrelated with the reverberation \( h \). Here boldface lower case letters denote \( N \)-dimensional vectors and \( N \) is the number of TRM elements.

In practice, a number of target-free reverberation returns \( x_i \) (i.e., snapshots) are collected to form a data covariance matrix \( \hat{R} \) and its eigen-decomposition:
\[ \hat{R} = \frac{1}{L} \sum x_i x_i^H = U \Lambda U^H + V \Omega V^H, \]  

where $H$ denotes a conjugate transpose, $L$ the number of snapshots, $A$ a diagonal matrix containing $K$ largest eigenvalues, and $U$ an $N \times K$ matrix of the corresponding eigenvectors ($u_i, i=1, \ldots, K$) spanning the $K$-dimensional reverberation subspace. Some of the eigenvalues may be zero so that $\hat{R}$ may be less than full (e.g., for a snapshot-deficient case when $L < N$).

For reverberation nulling, a complementary subspace that is orthogonal to the reverberation subspace is obtained in terms of an $N \times N$ projection matrix $P$ such that

\[ P = I - U U^H = I - \sum_{i=1}^{K} u_i u_i^H, \]

where $I$ is an identity matrix. It should be mentioned that the projection matrix can be deduced from the inverse of $\hat{R}$.
which arises in adaptive algorithms when the \((N-K)\) small eigenvalues are negligible as compared to the \(K\) significant eigenvalues.\(^9\)

Ideally the rank of \(\hat{R}\) will be equal to 1 (i.e., \(K=1\)) in a stationary environment since reverberation is treated as a single interference in Eq. (1). Thus, the first eigenvector \(u_1\) will be proportional to the transfer function vector \(h\). For a single snapshot case \((L=1)\), \(u_1\) is assumed approximately proportional to the transfer function vector \(h\) for a high reverberation-to-noise ratio.\(^2,3\) Our experiment produced eight target-free snapshots \((L=8)\) while the ER simulating a target was drifting along with the R/V Alliance. For a small number of snapshots, the first eigenvector alone may not necessarily represent the reverberation subspace due to eigenvalue spreading.\(^10\)

Since target-free observations are used to construct the projection matrix and the number of snapshots \((L=8)\) is much smaller than the number of degrees of freedom (DOF) equal to the number of active array elements \((N=26)\), any number of \(K \leq L\) can be used for the reverberation subspace which is confirmed in Sec. IV B. This is not surprising because the 26-element array covers the water column and provides the spatial diversity\(^17\) which allows for simultaneous focusing (or localization) on a target within the water column and the bottom interface. In other words, all the target-free reverberation is confined to the bottom interface and the remaining \((N-L)\) DOF subspace is sufficient to capture the signal component which is orthogonal to the reverberation.

When the echo plus reverberation returns are used to construct the projection matrix, however, \(K\) must be chosen carefully as discussed in the next subsection. Below we investigate the impact of \(L\), \(K\), as well as \(N\) on the detection performance using the 16 BS transmission data.

### B. Target detection

The projection matrix \(P\) can be applied directly to echo plus reverberation data in order to improve the target detectability. Since a priori knowledge of target range is not assumed, each segment of the reverberation data is transformed into the frequency domain by fast Fourier transform and is advanced by a sliding (moving) window. Specifically, the duration of the time window \(\tau\) is selected 1.3 times the pulse length \(\Delta = 100\) ms as suggested in Ref. 2 and each segment is advanced by 25 ms.

Figure 6 shows the first five eigenvalues of the data covariance matrix \(\hat{R}\) as a function of time (or equivalently range) from the eight target-free BS transmissions \((L=8)\) displayed in Fig. 4(a). As expected for a strong single interfe-

![Fig. 8. Eigenvalue spread (1–5) of the data covariance matrix \(\hat{R}\) from a total of eight \((L=8)\) echo plus reverberation returns as a function of time. The first eigenvalue looks similar to the one shown in Fig. 6. The incoherent average of the energy from Fig. 4(a) is superimposed with an offset of 80 dB (dotted line). On the other hand, the second eigenvalue shows a strong peak at 3.9 s at the range of the target.](image1)

![Fig. 9. Echo-to-reverberation enhancement after reverberation nulling from eight \((L=8)\) echo plus reverberation snapshots: (a) \(K=1\) and (b) \(K=3\). \(K=1\) still provides target detection comparable to one in Fig. 4(d) which uses target-free observations. However, the detection performance deteriorates with \(K=3\) by rejecting the signal component as well.](image2)
ence, the first eigenvalue is dominant and is about 10 dB higher than the second eigenvalue. The dotted line represents the average level of the incoherent energy in Fig. 4(a) superimposed with an offset of 80 dB below the first eigenvalue. It follows closely the first eigenvalue confirming that the first eigenvalue captures the reverberation. Due to the large number of DOF ($N=26$) and small number of snapshots ($L=8$) as discussed in Sec. IV A, it is found that any number of $K \approx 8$ provides similar performance.

The lower two plots of Fig. 4 show the results after reverberation nulling $|\mathbf{PR}|$ using $K=3$: (c) reverberation alone when $\mathbf{r}=\mathbf{x}$ and (d) echo plus reverberation when $\mathbf{r}=\mathbf{s}+\mathbf{x}$. Two observations can be made. First, the prominent reverberation returns in Fig. 4(a) have diminished and are flattened out in Fig. 4(c). Second, plot (d) clearly demonstrates improved target detectability after nulling at around 3.9 s (about 5 dB over the background) as compared to plot Fig. 4(b) before reverberation nulling. Note that after the projection operation the absolute level (dB) has no meaning in the lower two plots. It also should be mentioned that the passive reverberation nulling approach can be applied even when multiple targets are present at various ranges.

The impact of the number of snapshots $L$ is illustrated in Fig. 7 which compares results when (a) $L=1$ and (b) $L=8$. Since only a single eigenvalue is available for $L=1$, $K=1$ is applied to both cases for comparison purposes. While a single snapshot still provides reasonable performance suggesting a high reverberation-to-noise ratio of the data, the improvement using more snapshots is evident in Fig. 7(b).

Up to now, it is assumed that the target-free observations are available to construct the data covariance matrix $\hat{\mathbf{R}}$ and then the projection matrix for nulling. In practice, however, we may not know whether the measured reverberation contains a target echo. Consider the case when we have a total of eight echo plus reverberation returns. The observation vector then can be written as

$$\mathbf{x} = \mathbf{h} + \mathbf{s} + \mathbf{n}. \quad (4)$$

If the eigenvalues corresponding to reverberation and signal are separable, a projection matrix still can be derived by selecting an appropriate number of $K$ such that the $K$-dimensional subspace spans the reverberation alone but excludes the signal component.\textsuperscript{10} The first five eigenvalues are shown in Fig. 8 from the eight ($L=8$) echo plus reverberation returns. The first eigenvalue looks about the same as one in Fig. 6. On the other hand, the second eigenvalue shows a strong peak around at 3.9 s. This suggests that the first eigenvector $K=1$ spans the reverberation space while the second eigenvector represents the target space. Figure 9 compares results when (a) $K=1$ and (b) $K=3$ are employed to construct the projection matrix which is then applied to the individual echo plus reverberation returns. $K=1$ shows target detection comparable to the result shown in Fig. 4(d) which uses target-free observations. On the other hand, the detection performance deteriorates with $K=3$ since the resulting projection matrix rejects the target component as well.

Finally, we investigate the impact of the number of array elements used for processing the received time series. Recall that the full source array was used for the BS transmissions. Figure 10 shows the performance when $N=26$ (full), $N=14$ (half), and $N=6$ (quarter). The array elements are selected
from the bottom. The eight \((L=8)\) target-free snapshots are used to construct the data covariance matrix as before and \(K=1\). Half the array \((N=14)\) still shows target detection at 3.9 s while a false target emerges at around 2.1 s as well. With a further decrease down to \(N=6\), the target echo eventually disappears and the distinct peak at 2.1 s likely would lead to a false alarm.

V. CONCLUSION

Bottom backscattering potentially can be used as a surrogate probe source for reverberation nulling. A time-gated portion of the reverberation return from conventional BS transmissions provides an estimate of the transfer function between a TRM array and the corresponding range cell boundaries. Active reverberation nulling projects an excitation weight vector that is in the complementary subspace orthogonal to the focusing vector, minimizing the acoustic energy interacting with the boundaries in a specific range cell. However, the range over which boundary interaction is suppressed is limited and different excitation vectors must be transmitted for each range of interest. Alternatively, passive reverberation nulling applies an orthogonal projection onto the echo plus reverberation data to suppress the reverberation component without need for a specialized active retransmission. The signal processing employed essentially is equivalent to the orthogonal projection method developed in adaptive beamforming algorithms. The improved target detection resulting from passive reverberation nulling is demonstrated experimentally with reverberation data and an echo repeater simulating a target in shallow water.

ACKNOWLEDGMENT

This work was supported by the Office of Naval Research under Contract No. N00014-01-D-0.043-D06.