Multichannel array diagnosis using noise cross-correlation

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Abstract: A practical application of noise cross-correlation for the diagnosis of a multichannel ocean hydrophone array is derived. Acoustic data were recorded on a horizontal line array on the New Jersey Shelf while Tropical Storm Ernesto passed through. Results obtained from active source measurements reveal that signals from several hydrophones, which were recorded on certain channels before the storm, are recorded on different channels after the storm. Noise cross-correlation of data recorded during the storm show when, and in what manner, these changes took place.

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1. Introduction

Lobkis and Weaver[1] showed, both theoretically and experimentally, that the Green's function between two points, and hence the acoustic travel time between them, can be extracted from their temporal cross-correlation within a diffuse ultrasonic field. Since then, noise cross-correlation techniques and their applications have been explored in numerous areas.[2–8]

In recent years, ocean noise temporal cross-correlation has been explained theoretically,[9] and demonstrated experimentally.[10] Siderius *et al.*[11] applied the concept to passive fathometry, and showed that it can be used to approximate sea floor structure. Sabra *et al.*[12] used noise cross-correlation for array localization and self-synchronization. These studies all concluded that accurate direct path acoustic travel times between hydrophones can be obtained from noise cross-correlation in the ocean.

During the Shallow Water 2006 experiments, which were conducted off the New Jersey shelf, Tropical Storm Ernesto passed through the experimental area. Large sea state and wind conditions started to develop during the evening of 1 September, resulting in all experimental activities ceasing until 3 September. The acoustic arrays remained operative throughout this period. Analysis of experimental data recorded on a 20 hydrophone horizontal line array (HLA) after the storm revealed that several channels in the array had switched.

For the purpose of this express letter, *channel switching* means that the signals from a given hydrophone which were previously recorded on a certain channel, are subsequently recorded on a different channel; *hydrophone* refers to the physical transducer in the array; and *channel* refers to the recording medium where the data from a hydrophone were stored. Hydrophone and channel numbers matched upon deployment of the array [see Fig. 1(b)], but not after the channel switching occurred [see Figs. 1(c) and 1(d)].

This express letter describes how ambient noise cross-correlation of array data from the storm are used to diagnose a problem of channel switching that occurred between hydrophone pairs. When channel switching occurs, a set of two given channels begin to record data

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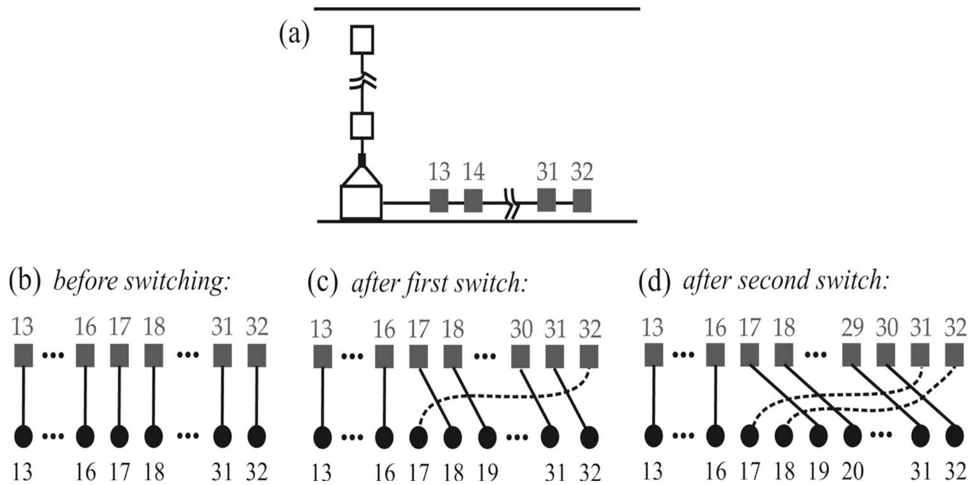

Fig. 1. (a) Array geometry. (b)–(d) Schematics showing the hydrophone-channel connections: (b) At deployment, (c) after the first switch, and (d) after the second switch.

from a different pair of hydrophones, and hence the interhydrophone travel time, determined from cross-correlation of the signals, will change. The estimated travel times, and specifically changes therein, are used to determine on which channel the data from each hydrophone are being recorded at any given time during the day. Consequently, the time and manner in which the channel switching occurs is ascertained.

2. Analysis of recorded data

The array [see Fig. 1(a)] is an L-shaped array with a 256-m-long horizontal portion (HLA) consisting of 20 hydrophones with tapered spacing.

Preliminary analysis of acoustic data (see Sec. 2.1) from active sources collected throughout the experiment shows that switching of channels occurred. Since no active source experiments were undertaken during the storm, further details of the switching could not be determined using traditional techniques; however, ambient noise cross-correlations (see Sec. 2.2) show when, and in what manner, the switching occurred.

2.1 Active sources

Data from both broadband pulses and combustive sound sources show that the signals recorded on each channel correspond to the correct hydrophones before the storm [see the *before switching* configuration of Fig. 1(b)]. The signal from a broadband 1100–2950 Hz energy pulse, recorded at 6:04 Z (Zulu) on 31 August, 21° from the HLA axis, and 1385 m from the closest hydrophone (hydrophone 32), was projected to the on-axis direction. The envelope of the projected signal received by each HLA channel (directly interchangeable with hydrophone numbers for this case) is shown in Fig. 2(a). The time of arrival is plotted relative to the first direct arrival. Several reflected arrivals are observable on each channel at times later than the direct. As expected, each arrival is received first by the channel corresponding to the closest hydrophone (channel 32), and the arrival times increase as the channel number decreases. The time interval between arrivals on each channel increases due to tapering of the array spacing.

After the storm, data from both linear frequency modulated (LFM) sweep sources and combustive sound sources indicated that some switching of channels occurred. The match filtered signal from a 1100 to 2900 Hz 1 s duration LFM source, held 10 m below the water surface, recorded at 14:40 Z on 3 September, on-axis with the HLA, and 150 m from the closest hydrophone, is shown in Fig. 2(b). The signals recorded on each channel no longer correspond to the correct hydrophones. The data from hydrophones 31 and 32 are recorded on channels 17

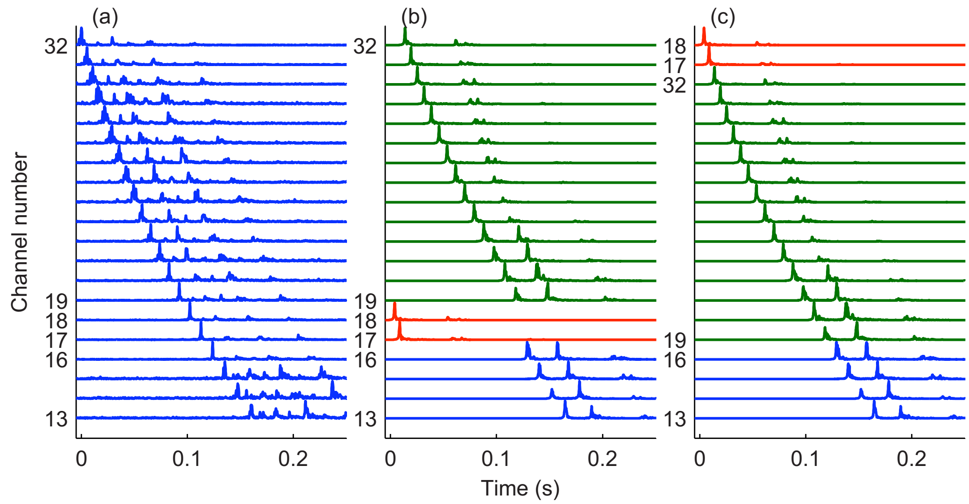

Fig. 2. (Color online) Envelope of the signal recorded on each channel from active source testing (a) before the storm [31 August, 6:04 Z], and (b) after the storm [3 September, 14:40 Z]. (c) Signal envelope from after the storm with channels resorted. Channels 14–15 and 20–31 are unnumbered, but are in order between 13 and 16, and between 19 and 32, respectively.

and 18, respectively, and the data from hydrophones 17 to 30 are all recorded two channels higher than expected [see Fig. 1(d)]. Figure 2(c) shows the data after re-sorting the channels so that the data from hydrophones 13 through 32 are in order. The arrival times and the manner in which the shape of the envelope evolves are consistent, which shows that data recorded after switching of the channels occurred are reliable (i.e., acoustic data from each hydrophone are still being recorded).

2.2 Ambient noise cross-correlations

The cross-correlation between two hydrophones, denoted A and B, as a function of time delay, t, is defined as

$$C_{AB}(t) = \int_{-\infty}^{\infty} p_A(t+\tau)p_B(\tau)d\tau, \tag{1}$$

where p is the pressure recorded at each hydrophone, and τ is time. It has been shown[9,13] that the arrival-time structure of the Green's function, between hydrophones A and B, G_{AB} defined as the signal which would be received at A given a unit impulsive source at B, can be extracted from the time derivative of the ocean noise cross-correlation function:

$$\frac{\partial C_{AB}(t)}{\partial t} \simeq -[G_{AB}(t) - G_{AB}(-t)]. \tag{2}$$

The raw cross-correlation, rather than its time derivative, is often used as an approximation to the Green's function,[10,14] and for a finite bandwidth signal this can be a good approximation, since the cross-correlation and its derivative closely resemble one another. However, if exact arrival times are desired, the cross-correlation time derivative should be employed, as this corrects for the $\pi/2$ phase difference between the raw cross-correlation arrival peak, and that of the Green's function.[9]

Ship-dominated 20–100 Hz noise was recorded throughout the day that Tropical Storm Ernesto passed through. After preprocessing the data, cross-correlation periods of 6 h 24 min, which corresponds to the length of a single data file, were employed. Since the cross-correlation wave forms are relatively narrow, it is sufficient to consider the raw cross-

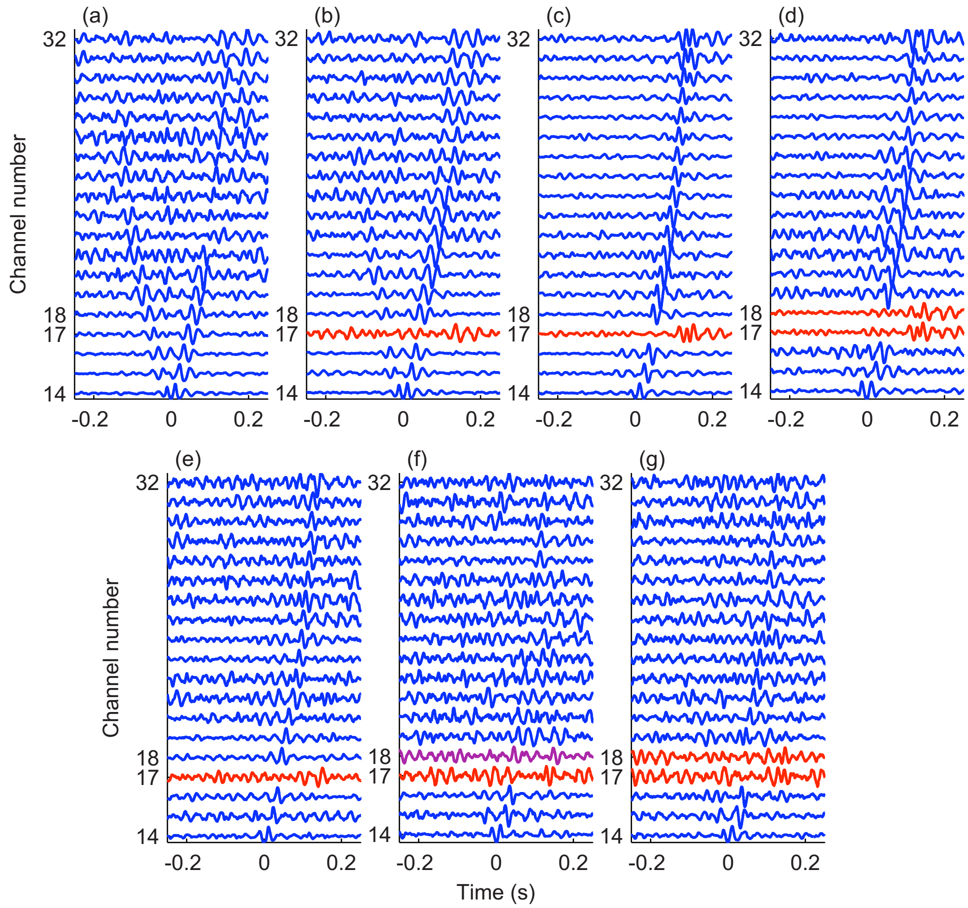

Fig. 3. (Color online) Short time cross-correlation (6 h 24 min) between channel 13 (first HLA hydrophone) and all other channels from the time period surrounding the first switch (a) 7:07:37 Z and (b) 7:14:01 Z, and from the time period surrounding the second switch (c) 12:08:40 Z and (d) 12:15:05 Z. (e)–(g) Cross-correlations 20 s long at 12:14 Z for times (e) 20–40 s, (f) 30–50 s, and (g) 40–60 s.

correlations for the purpose of determining which channels are recording data from which hydrophones. Due to the short cross-correlation times, peak amplitudes of the postprocessed data were prone to bias from high amplitude directional sources. However, even if the source field is not isotropic, the time of the cross-correlation peak between the hydrophones increases with distance. Examination of the raw cross-correlations over the entire day revealed three main findings: (a) the channel switching occurred in two steps; (b) an approximate time at which each switch occurred can be determined; and (c) the raw signals, and hence the signal cross-correlations, recorded for a significant time period before and after each switch, exhibit high levels of noise on the higher channels.

Cross-correlations from times prior to and after each switch occurred are shown in Figs. 3(a)–3(d). Figure 3(a), which is the cross-correlation starting at 7:07:37 Z, shows that the channels are in order, and the cross-correlation peak corresponds to a move-out velocity of approximately 1500 m/s, as expected. The cross-correlation of data starting at 7:14:01 Z [see Fig. 3(b)] shows an anomaly in the signal recorded by channel 17. The signal does show a small peak at the expected move-out velocity; however, the major peak occurs at a time of just under 0.2 s, which is the expected cross-correlation time for channel 32. The signals recorded on channels 18 through 32 exhibit major peaks corresponding to those expected for one channel lower than their assigned values. These results suggest that channel 17 switched within the period 7:17 Z±3 min, the relative peak amplitudes indicating that the switch was closer to the start of this time period. Note that the cross-correlations for channels above 17 exhibit high levels of noise. High noise levels were, in fact, observed on channels 18–32 for a 2 h period surrounding this time (5:40–7:40 Z), suggesting that the channel switching and the increase in noise are linked. The hydrophone-channel connections after this first switch are shown in Fig. 1(c).

Results of cross-correlation of data starting at 12:08:40 Z are shown in Fig. 3(c). Channel 17 is still the only channel to have switched. Cross-correlation of data immediately following this, starting at 12:15:05 Z [see Fig. 3(d)], suggests that channel 18 has also switched. Now channels 17 and 18 are recording data from hydrophones 31 and 32, and channels 19–32 are recording data from two hydrophones less than their number. This configuration matches the "after switching" description of Sec. 2.1 [see Figs. 1(d) and 2(b)]. Cross-correlations with higher numbered channels exhibit less noise than during the first switch, and high noise levels were only observed for a few minutes around the time of the second switch.

Cross-correlations over shorter time periods were employed to narrow down the time window during which the second switch occurred. Cross-correlations of 20 s duration were calculated from 12:08:40 to 12:21:29 Z. Three results from the minute of 12:14 Z are shown in Figs. 3(e)–3(g): (e) 20–40 s, (f) 30–50 s, and (g) 40–60 s. Due to the shorter duration of the cross-correlation time, the cross-correlations exhibit high noise levels; however, the peak arrivals can still be observed. The first cross-correlation [Fig. 3(e)] suggests that channel 17 has switched but 18 has not. The second cross-correlation [Fig. 3(f)] is the least clear, but suggests that the switch occurs during this time period, since both the true and delayed arrival are seen. The third cross-correlation [Fig. 3(g)] also exhibits the true and delayed arrival; however, the delayed peak is more dominant, suggesting that the switch occurred closer to the start of the cross-correlation period. The likely time interval during which the second channel switching occurred is thus 12:14:45 Z±5 s.

Once the switch times had been determined, data from the entire day of 2 September were correlated in three time segments: (a) immediately before either switch, (b) after the first switch but before the second switch, and (c) immediately after the second switch. If the channels are re-sorted so that the data from hydrophones 13 through 32 are in order, and then plotted as a function of distance from hydrophone 13, the cross-correlation peaks are seen to increase linearly in time with distance along the array, in agreement with the results previously described [see Figs. 4(a)–4(c)]. The noise levels are lower than those in Fig. 3 due to the longer cross-correlation periods. The envelopes of the time derivatives of the cross-correlation functions, which, as previously mentioned, relate to the arrival times between hydrophones, are shown in Figs. 4(d)–4(f) [corresponding to data in Figs. 4(a)–4(c), respectively]. The simulated travel times between hydrophones (determined using OASES[15]) are also shown. The envelope peaks are in agreement with the direct arrival, and also with the surface reflected arrival at greater distances (the surface reflected arrival is not seen at closer distances due to the steeper grazing angles, which are accompanied by greater bottom loss). Although not shown, cross-correlations between all other channels in the HLA are in complete agreement with the findings presented here.

3. Conclusion

Results from active source experiments near the array prior to and after the day Tropical Storm Ernesto passed through the region (2 September, 2006) showed that some channels had switched during the storm.

Ambient noise cross-correlation of data from 2 September was successfully employed to determine more information about the nature of the channel switching. The cross-correlation analysis suggested that the switching occurred in two distinct stages. The mechanism which occurred at each stage was identical; the channel that was recording the data of hydrophone 17 started recording data from hydrophone 32, and the channels recording data from hydrophones 18 through 32 all moved down one hydrophone [see Figs. 1(c) and 1(d)]. The inferred time

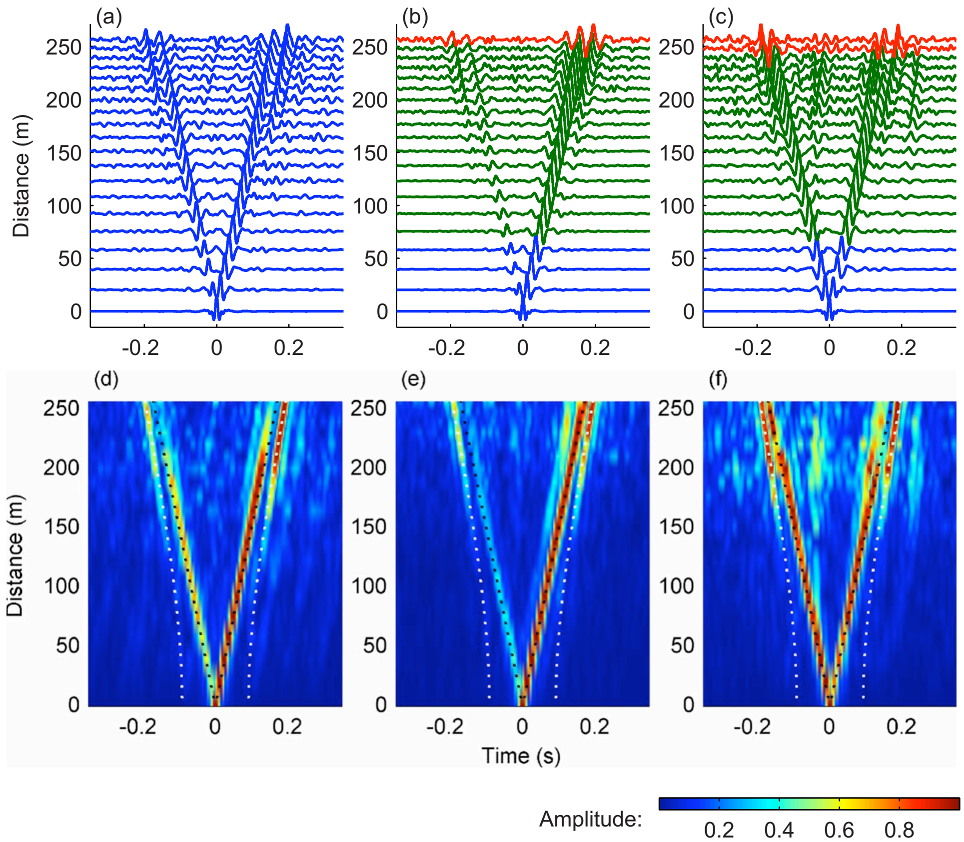

Fig. 4. (Color online) (a)–(c) Cross-correlations between channel 13 (first HLA hydrophone) and all other channels after re-sorting the channels, plotted as a function of distance from hydrophone 13 [(a) before, (b) between, and (c) after switches]. (d)–(f) Normalized envelopes of the cross-correlation function time derivatives, with simulated direct (black dotted lines) and surface reflected path travel times (white dotted lines) [(d) before, (e) between, and (f) after switches].

intervals during which each switch happened were narrowed down to the periods 7:17 Z$\pm$3 min and 12:14:45 Z$\pm$5 s. Elevated noise levels were observed on each channel for a significant time period surrounding each switch. The noise levels were especially high during the first switch, making it difficult to narrow down the time of the switch to as small a time window as was obtained for the second switch. Longer time period cross-correlations from before, between, and after the switches occurred, supported the findings. With the channels re-sorted to the correct hydrophones, the cross-correlation function time-derivative envelopes showed accurate arrival time structure.

Acknowledgments

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