Diver Detection and Localization Using Passive Sonar

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ABSTRACT

An open-circuit scuba diver's acoustic signature (radiated sound) consists predominately of a sequence of regularly spaced wideband pulses each corresponding to the inhaling phase of the diver's breathing cycle. A cyclic frequency analysis of the output signal from a single hydrophone leads to the automated detection of the diver and an estimate of the diver's breathing rate. Measurement of the differential time of arrival (DTOA) of the radiated sound at a pair of widely separated hydrophones requires computation of the wideband cross-ambiguity function. By fitting a DTOA model to the measurements for pairs of sensors over a sufficiently long period of time enables estimation of the diver's motion parameters. Results are presented for real data collected in a shallow water experiment where an open-circuit scuba diver swam at constant speed and altitude above and along the axis of a horizontal linear array which consisted of eight hydrophones uniformly spaced at 14 m and located 1 m above the sea floor.

INTRODUCTION

Divers and small vessels when operating with harmful intent are potential threats to naval bases, civilian port facilities and critical harbour infrastructure. Both passive and active sonar systems can be used to provide surface and subsurface surveillance against these asymmetric threats. It was demonstrated using real data that a high-frequecy active sonar was able to detect, localize and track small fast surface craft and divers in a harbour environment by processing the sonar return signals (Lo & Ferguson 2004, Ferguson & Lo 2011). Also, the intense broadband underwater sound generated by a surface craft's propeller cavitation enabled the passive detection and localization of the craft using hydrophones (Ferguson & Lo 2011, Lo & Ferguson 2011). Using real data, this paper studies the detection and localization of open-circuit scuba divers using passive sonar. The data used in this study were collected in a shallow water experiment, where an open-circuit scuba diver swam at a constant speed and altitude above and along the axis of a horizontal linear array which consisted of eight hydrophones uniformly spaced at 14 m and located 1 m above the sea floor.

An open-circuit scuba diver's acoustic signature (radiated sound) consists predominately of a sequence of regularly spaced wideband pulses each corresponding to the inhaling phase of the diver's breathing cycle. The primary source of these pulsed acoustic emissions is the scuba equipment's high pressure regulator where expansion of the compressed air from the tank produces turbulent air flow pressure fluctuations that excite structural vibrations of the regulator's valve and channels (Donskoy, Sedunov, Sedunov & Tsionskiy 2008). It is shown that the periodicity of the diver's acoustic signature is readily observed on the output spectrogram of a single hydrophone, and a cyclic (or modulation) frequency analysis of the hydrophone output signal leads to the automated detection of the diver and an estimate of the diver's breathing rate. The conventional method for cyclic frequency analysis is DEMON processing (Hanson, Antoni, Brown & Emslie 2008, Chung, Sutin, Sedunov & Bruno 2011), which was adopted by other researchers for automated diver detection (Stolkin, Sutin, Radhakrishnan, Bruno, Fullerton, Ekimov & Raftery 2006, Lennartsson, Dalberg, Persson & Petrovic 2009). Another method for cyclic frequency analysis is cyclostationary processing (Hanson, Antoni, Brown & Emslie 2008, Owsley, Atlas & Heinemann 2005). Experimental results for both methods are compared in this paper.

An acoustic source (diver) can be localized by estimating the differential times of arrival (DTOA) of the signal at pairs of widely separated hydrophones using the generalized cross-correlation method (Carter 1981). (Note that DTOA is often simply referred to as time delay.) In this paper, the hydrophone output data are processed in small blocks of short duration to estimate the temporal variation of the DTOA of the signal at each pair of adjacent hydrophones. During the exhaling time intervals, the signal-to-noise ratios (SNRs) are low which leads to noisy DTOA estimates. Therefore, DTOA estimation is restricted to the inhaling time intervals during which the SNRs are high. However, the DTOA estimates obtained during the inhaling time intervals for any pair of hydrophones become noisy when the source is moving between the two hydrophones, despite the high SNRs at the outputs of the hydrophones. This problem is due to the relative time-scaling effect (often referred to as *differential Doppler*), which results in a loss of coherence between the signals received by the hydrophone pair (Patzewitsch, Srinath & Black 1979, Betz 1985). The problem is remedied by using the wideband cross-ambiguity function which is equivalent to wideband cross-correlation with differential Doppler compensation (Ferguson & Lo 1999). The DTOA measurements from two pairs of adjacent hydrophones are then processed using a nonlinear least-squares method to estimate the diver's swimming speed, altitude and time of closest point of approach (CPA) to the reference hydrophone.

SHALLOW WATER EXPERIMENT

An experiment was conducted in a shallow water environment, where a horizontal linear array consisting of eight hydrophones uniformly spaced at 14 m was located 1 m above the sea floor, and an open circuit scuba diver swam at a constant speed (~ 0.5 m/s) and altitude (~ 1 m) above and along the axis of the array – see Fig. 1. The water depth was 20 m. The output of each hydrophone was sampled at a frequency f_s of 250 kHz. The first set of data was collected over a period of 333 s when the diver swam from the right of sensor 1 to the left of sensor 8 (transit 1) and then made a U turn after passing sensor 8. The second set of data was collected over a period of 282 s when the diver swam from the left of sensor 8 to the right of sensor 1 and then made a U turn after passing sensor 1 (transit 2). In this paper, experimental results are presented only for the first data set (transit 1) as results for the second data set (transit 2) are similar.

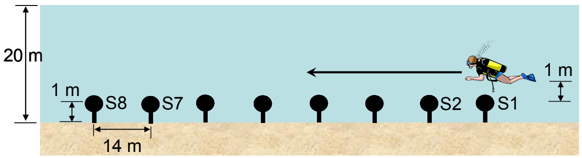
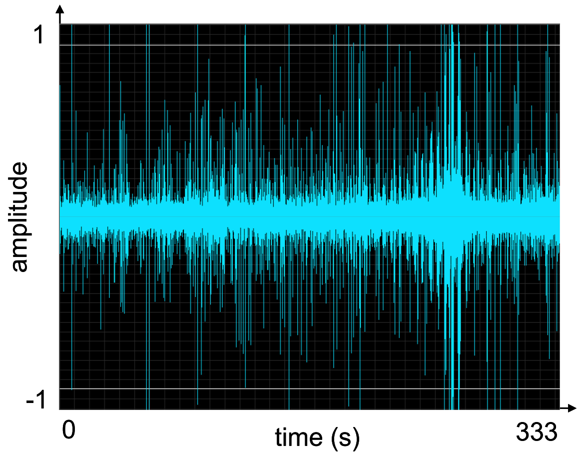
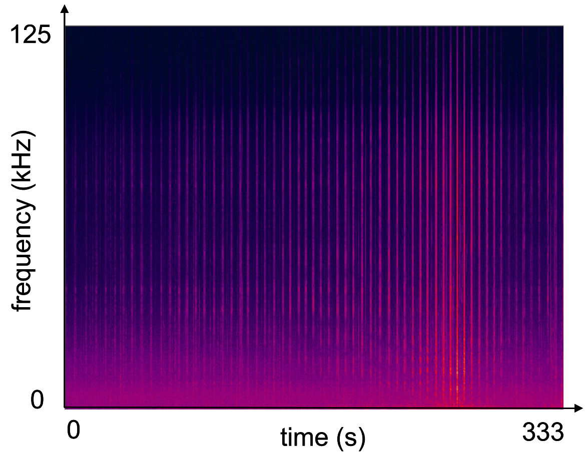


Fig. 1. Geometry of hydrophone array and diver trajectory in the shallow water experiment.



(a)



(b)

Fig. 2 (a) Output waveform and (b) output spectrogram of hydrophone 8 for diver transit 1.

Figures 2(a) and (b) show the respective output waveform (time series) and output spectrogram (time-frequency distribution) of a particular hydrophone (sensor 8) for diver transit 1. It can be observed from Fig. 2(b) that the hydrophone output signal consists of a sequence of (almost) regularly spaced wideband pulses which is most notable in the 35-80 kHz frequency band. The background noise predominates below 20 kHz. Biological transients generated by snapping shrimp are also present. The signal pulse is strong (as indicated by the higher-intensity color) when the diver is close to the hydrophone (around 261 s). This periodic wideband pulse sequence forms the diver's acoustic signature, and each of the periodic pulses corresponds to the inhaling phase of the diver's breathing cycle. The diver's acoustic signature is obscured by the background noise in the time series shown in Fig. 2(a).

DIVER DETECTION

Two methods are considered for diver detection, namely, DEMON processing and cyclostationary processing. Both methods exploit the periodicity of the diver's acoustic signature. In DEMON processing, the envelope of the periodic wideband pulse sequence received at a hydrophone is extracted by first filtering the hydrophone output data with a suitable bandpass filter (to suppress the background noise), then applying the Hilbert transform to the filtered data to compute the complex analytic signal, and finally subsampling (with an anti-aliasing filter) the magnitude of the analytic signal at a frequency α_s that satisfies the condition $2f_b < \alpha_s << f_s$, where f_b is the diver's breathing rate (typically 0.1-0.5 Hz). A cyclic (or modulation) frequency spectrum is then computed by taking the Fourier transform of the (subsampled) envelope. As the possible breathing rates of divers range from 0.1 to 0.5 Hz, a peak appearing within this frequency range in the cyclic frequency spectrum indicates the presence of a diver, and the location of the peak provides an estimate of the diver's breathing rate.

An alternative approach to diver detection is cyclostationary processing. First, the spectrogram $X(t,f)$ of the hydrophone output signal is computed. Then for each frequency f, a Fourier transform of $\log|X(t,f)|$ is taken along the time axis to produce a cyclic frequency spectrum: $S(\alpha,f) = F\{\log|X(t,f)|\}$, where F is the Fourier transform operator, and α denotes cyclic frequency. Finally the cyclic frequency spectra are averaged over all frequencies f. As for DEMON processing, the sampling frequency of $X(t,f)$ along the time axis is denoted by α_s which satisfies the condition $2f_b < \alpha_s << f_s$. A peak appearing within the frequency range from 0.1 to 0.5 Hz in the averaged cyclic frequency spectrum indicates the presence of a diver, and the location of the peak provides an estimate of the diver's breathing rate.

In practice, the output data from a hydrophone are processed in blocks each consisting of M samples. The diver's breathing rate is assumed to be constant over the duration of a data block, but may vary from block to block. An estimate of the diver's breathing rate is computed for each data block using DEMON or cyclostationary processing. The estimate can be updated at a faster rate of every L/f_s seconds by overlapping every two adjacent blocks with $M-L$ samples $(L \le M)$. In the experiment, the following parameter values were used: M = 8,388,608 samples (corresponding to approximately 33.55 s) and $L = M/4$. For DEMON processing, the bandpass filter had a passband from 35 to 80 kHz and the sampling frequency α_s for the signal envelope was 6.25 Hz. For cyclostationary processing, the spectrogram $X(t,f)$ of the hydrophone output signal was computed using the fast Fourier transform (FFT) and a window size m of 32,768 samples (~ 0.131 s) with no overlap between adjacent windows, which implied that the sampling frequency α_s for $X(t,f)$ along the time axis was equal to $f_s/m \approx 7.63$ Hz.

Figure 3 shows the variation with time of the normalized cyclic frequency spectra of the output data from sensor 8, computed using (a) DEMON processing and (b) cyclostationary processing, for transit 1. At each time instant, there appear to be one strong peak corresponding to the diver's breathing rate and two weaker peaks representing the higher harmonics. Based on these observations, the diver detection probability at any time instant may be improved by seeking two or three harmonically related peaks instead of a single peak within an appropriate frequency range. Figure 4 shows the estimates of the diver's breathing rate versus time obtained for transit 1 using both methods, and they are in good agreement. Similar results have been obtained for transit 2.

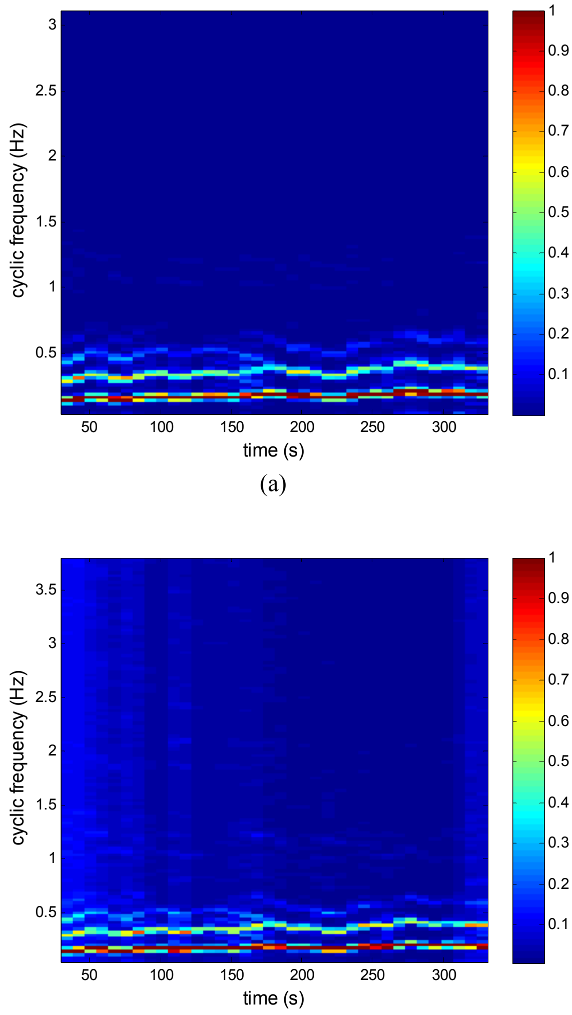


Fig. 3. Variation with time of the normalized cyclic frequency spectra of the output data from hydrophone 8, computed using (a) DEMON processing and (b) cyclostationary processing, for transit 1.

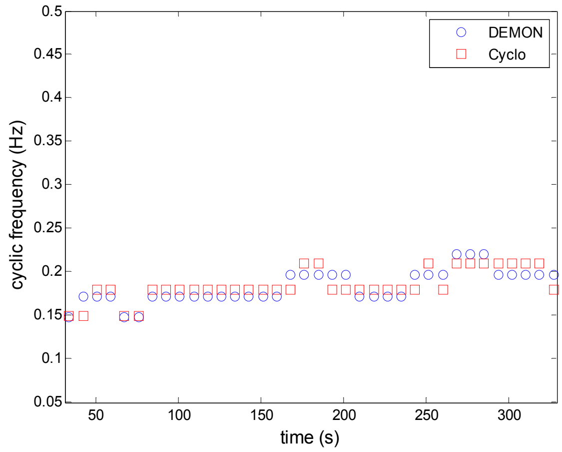


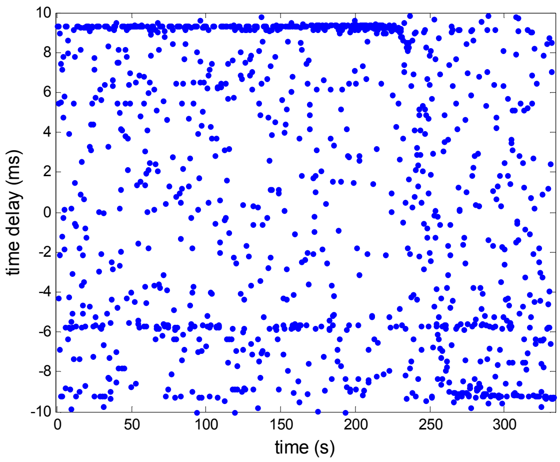
Fig. 4. Estimates of diver's breathing rate versus time obtained for transit 1 using both methods of DEMON and cyclostationary processing.

DTOA ESTIMATION

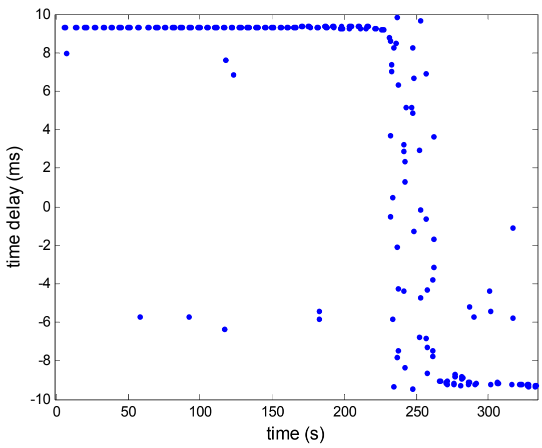
An acoustic source can be localized using DTOA (or time delay) measurements from pairs of widely separated hydrophones, which in turn can be obtained using the generalized cross-correlation method. For non-stationary sources such as divers, the DTOA of the signal at a hydrophone pair varies with time as the source moves from one position to another. In the experiment, in order to estimate the temporal variation of the DTOA of the signal at each pair of adjacent hydrophones, the hydrophone output data were processed in non-overlapping blocks, each consisting of 65,536 samples (~ 0.262 s). The data block from one sensor was cross-correlated with the corresponding data block from an adjacent sensor using the phase transform prefiltering technique, which suppressed ambiguous peaks in the cross-correlation function caused by strong narrowband interference. The generalized cross-correlation processing was implemented in the frequency domain using the FFT with a spectral window from 35 kHz to 80 kHz. The time lag at which the cross-correlation function attained its maximum value provided an estimate of the DTOA of the signal at a given hydrophone pair. Figure 5(a) shows the DTOA estimates obtained by processing the output data from the hydrophone pair (8,7) for transit 1. During the time intervals when the diver is exhaling, a large number of noisy DTOA estimates occur due to low SNRs. Therefore, DTOA estimation should be restricted to the inhaling time intervals during which SNRs are high.

The inhaling time intervals observed at a given hydrophone can be estimated by measuring the variation with time of the integrated output energy of the hydrophone over a certain frequency range where the SNR is high. Figure 6(a) shows the integrated output energy (obtained by integrating $|X(t,f)|^2$) of sensor 7 over the frequency range from 35 to 80 kHz as a function of time for transit 1. The integrated output energy is high during the inhaling time intervals and low during the exhaling time intervals. The presence of broadband impulsive noise sometimes raises the level of the integrated output energy for a short time during the exhaling time intervals. In order to estimate the inhaling time intervals, the integrated output energy at each time instant is normalized by the median of its surrounding values (which effectively removes the effect of the exhaling noise). Figure 6(b) shows the normalization result of Fig. 6(a). The normalized integrated output energy is then compared with a preselected threshold (3 dB for the experiment) and set to unity if it exceeds the threshold and zero otherwise. This results in a sequence of rectangular pulses (which are not necessarily equal in width). The width of each pulse represents an estimate of either the length of an inhaling time interval or the duration of an impulsive noise event. Those rectangular pulses with a width smaller than a preselected threshold (1 s for the experiment) are regarded as being associated with impulsive noise and thus discarded. The durations of the remaining rectangular pulses provide estimates of the inhaling time intervals.

The inhaling time intervals observed at sensor 7 for transit 1 were estimated using the above method, and Fig. 5(b) shows the DTOA estimates from the hydrophone pair (8,7) during the inhaling time intervals. The number of noisy DTOA estimates in Fig. 5(b) is much smaller when compared with Fig. 5(a) which shows the DTOA estimates from the same hydrophone pair during the entire observation period of 333 s.

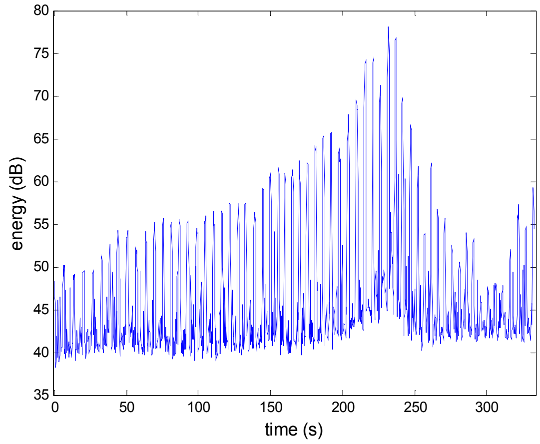


(a)

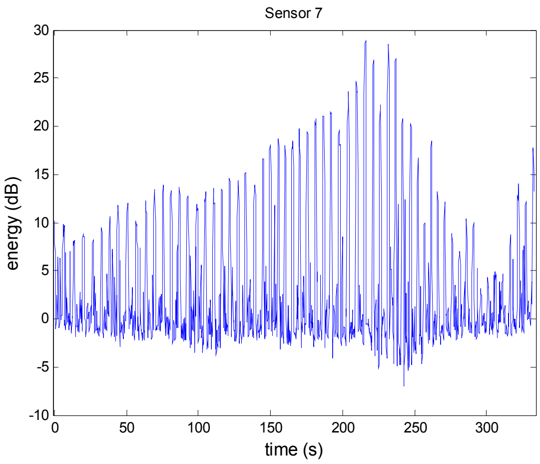


(b)

Fig. 5. (a) DTOA estimates obtained during the entire observation period of 333 s by processing the output data from hydrophone pair (8,7) for diver transit 1 using generalized cross-correlation. (b) DTOA estimates obtained during the inhaling time intervals only.



(a)



(b)

Fig. 6. Integrated output energy of sensor 7 over the frequency range from 35 kHz to 80 kHz as a function of time for diver transit 1. (a) Before normalization. (b) After normalization.

DIFFERENTIAL DOPPLER COMPENSATION

Note that the DTOA estimates (obtained during the inhaling time intervals) in Fig. 5(b) are noisy over the observation period from 230 s to 270 s, despite the high SNRs. These noisy DTOA measurements are attributed to the relative time-scaling effect as explained below. It can be deduced from Fig. 7(a) that the diver was passing over the hydrophone pair during this observation period (230-270 s) as the DTOA estimate was changing from positive to negative. It is known that when a sound source is passing over a pair of acoustic sensors, the source motion with respect to each sensor results in a relative time scaling (often referred to as *differential Doppler*) between the signals received by the sensor pair (Ferguson & Lo 1999). Thus, the source signal at the output of one sensor can be modelled as a constant time-scaled and time-delayed version of the other over *a short time interval*:

$$x_i(t) = s(t) + n_i(t)$$
$$x_j(t) = s\left(\frac{t-\beta}{\alpha}\right) + n_j(t) \quad (1)$$

where $s(t)$ is the source signal, α and β are the relative time scale (RTS) and DTOA (or time delay) respectively,

$x_i(t)$ is the output of sensor *i*, and $n_i(t)$ is additive noise at sensor *i*. Both α and β vary with time due to the source motion, but are assumed to be locally constant over short time intervals. Equations (1) can be written as

$$\begin{aligned} x_i(t) &= s(t) + n_i(t) \\ x_j(t) &= s[t-(at+b)] + n_j(t) \end{aligned} \tag{2}$$

where $a = 1 - 1/\alpha$, $b = \beta/\alpha$, and $at + b$ is the equivalent linear time-varying DTOA.

The RTS α in (1) can have significant impact on the estimation of the DTOA β using the generalized cross-correlation method as it can result in a loss of coherence between the signals received by the two sensors and consequently a noisy DTOA estimate. It has been shown that if the change $\Delta\beta$ in DTOA during the integration time ΔT of the cross-correlation processing is larger than the correlation time τ_s of the source signal, then the DTOA estimate will be in error (Adams, Kuhn & Whyland 1980). Consider the hydrophone pair (8,7) in the experiment: $i = 7$ (sensor 7), $j = 8$ (sensor 8). For both diver transits 1 and 2, the integration time $\Delta T \approx 0.262$ s, the correlation time of the source signal $\tau_s \approx 12.5$ μs, the diver's swimming speed $v \approx 0.5$ m/s, and the speed of sound propagation in water $c = 1520$ m/s. As the altitude of the diver relative to the axis of the hydrophone pair (~1 m) is much smaller than the hydrophone spacing (14 m), at the time when the diver is equidistant from the two hydrophones, the change $\Delta\beta$ in DTOA during the integration time ΔT is approximately equal to $\pm 2v\Delta T/c$ depending on whether the diver moves toward sensor 7 (transit 2) or sensor 8 (transit 1) during the integration time. In both cases, $|\Delta\beta| \approx 17.2$ ms, which is much larger than the correlation time of the source signal (12.5 μs), and thus the DTOA estimate is in error.

From (2), the change $\Delta\beta$ in DTOA over a time period of ΔT is equal to $a\Delta T$. Equating this expression for $\Delta\beta$ with $\pm 2v\Delta T/c$ gives $a \approx \pm 2v/c$, and so the relative time scale $\alpha = 1/(1-a) \approx 1 \pm 2v/c \approx 1.001$ or 0.999. These are the minimum and maximum values of α for transits 1 and 2 of the diver respectively. (These values can also be derived by assuming that the received signal at one sensor experiences the negative down Doppler while that at the other sensor experiences the positive up Doppler.) Despite their small deviations from unity, their adverse effect on DTOA estimation is large due to the large time-bandwidth product $\Delta T/\tau_s$. The RTS attains its maximum or minimum value when the diver is equidistant from the two hydrophones. At other times (when the diver is nearer to either of the two hydrophones) during the diver transit, the change $\Delta\beta$ in DTOA during the same integration time ΔT is smaller in magnitude, and the RTS α is closer to unity. If the diver is some distance away from the hydrophone pair, then $\Delta\beta \approx 0$, $a \approx 0$, and $\alpha \approx 1$.

A good estimate of the DTOA β can be obtained by cross correlating the outputs of the two sensors when the RTS α is essentially unity (or more accurately when $\Delta\beta << \tau_s$), which occurs when the source is some distance away from the sensor pair. In Fig. 5(b), this corresponds to the time periods 0-230 s and 270-333 s. The accuracy of the DTOA estimate degrades when α departs from unity, which occurs when the source is passing over the sensor pair. In Fig. 5(b), this corresponds to the time period 230-270 s. To remedy this problem, the mismatch between the time scales of the received signals at the two sensors must be compensated for prior to cross correlating the sensor outputs. However, since α is not known *a priori*, it must be estimated, along with β. Define the wideband cross-ambiguity function as

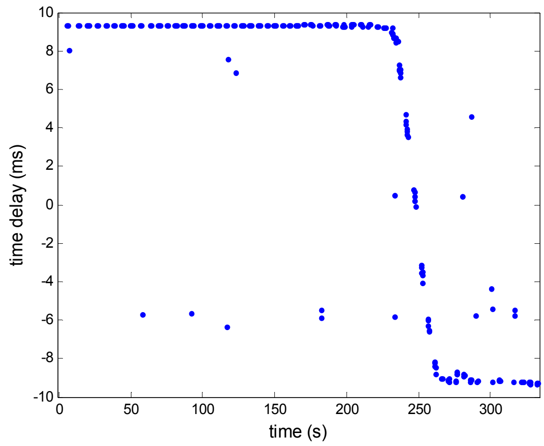
$$A_{ji}(\tau,\sigma) = \frac{1}{\sqrt{\sigma}} \int_{-\infty}^{\infty} x_j(t)\, x_i^*\!\left(\frac{t-\tau}{\sigma}\right) dt \tag{3}$$

where * denotes complex conjugation and $\sigma > 0$. Both β and α are estimated jointly by finding the values of τ and σ that maximize $A_{ji}(\tau,\sigma)$, that is, the estimates of β and α are given by

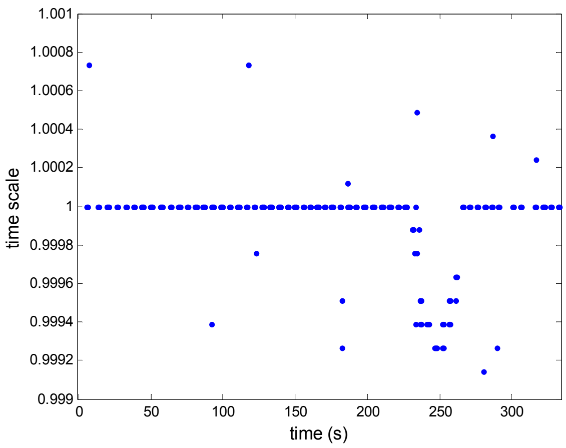
$$(\hat{\beta},\hat{\alpha}) = \arg\max_{\tau,\sigma} A_{ji}(\tau,\sigma)\,. \tag{4}$$

The wideband cross-ambiguity function $A_{ji}(\tau,\sigma)$ at a given value of τ and σ is computed by first generating the time-scaled replica $x_i(t/\sigma)$ using the discrete Fourier transform interpolation method and then correlating $x_i(t/\sigma)$ with $x_j(t)$ using the FFT (Ferguson & Lo 1999). The maximization of $A_{ji}(\tau,\sigma)$ is done by performing a two dimensional search over all possible values of τ and σ. This method of estimating α and β is equivalent to wideband cross-correlation with differential Doppler (or RTS) compensation.

The method was used to re-process the output data from each pair of adjacent hydrophones of the experimental linear array in non-overlapping blocks, with σ being assigned the following set of discrete values: $\sigma_p = 1 + p/L$, where $L = 65{,}536$ is the number of samples in each data block and $p = 0, \pm 8, \pm 16, \ldots, \pm 64$. Figure 7(a) shows the DTOA estimates from the hydrophone pair (8,7) during the inhaling time intervals for transit 1. Figure 7(b) shows the corresponding RTS estimates, which are essentially unity during the time periods 0-230 s and 270-333 s (indicating that the diver is some distance away from the hydrophone pair), and vary from about 0.9992 to 1 during the time period 230-270 s (indicating that the diver is passing over the hydrophone pair). At about 250 s, the RTS estimate has a minimum value and the DTOA estimate is zero (indicating that the diver is equidistant from the two hydrophones). Comparing Fig. 7(a) with Fig. 5(b) indicates that much better DTOA estimates are obtained during the time period 230-270 s when the method of wideband cross-correlation with RTS compensation is used for DTOA estimation. The remaining erroneous DTOA estimates in Fig. 7(a) are due to the presence of extraneous impulsive noise in the inhaling time intervals.



(a)



(b)

Fig. 7. Results of wideband cross-correlation with RTS compensation. (a) DTOA estimates from hydrophone pair (8,7) during the inhaling time intervals for transit 1. (b) The corresponding RTS estimates.

MOTION PARAMETER ESTIMATION

For an underwater acoustic source passing over a planar array of widely separated hydrophones along a straight line at a constant speed and a constant altitude, the complete set of five source motion parameters (which specifies the linear trajectory of the source) can be estimated using DTOA measurements from multiple pairs of hydrophones. However, in the experiment, the diver swam along and over the axis of a linear hydrophone array at a constant speed. In this case, the trajectory of the diver is specified by the diver's swimming speed v, altitude h relative to the array axis, and time τ_c of CPA to a reference hydrophone. These three source motion parameters can be estimated using DTOA measurements from one or more pairs of adjacent hydrophones of the linear array.

Without loss of generality, assume that the axis of the linear hydrophone array coincides with the x-axis. The diver's swimming speed v is positive if the diver travels in the $+x$ direction, and negative otherwise. For a given hydrophone pair (j,i), where $1 \le i, j \le N$ with $N = 8$ being the number of sensors in the linear array, the DTOA of the signal at the two sensors is given by

$$D_{ji}(t) = [R_j(t) - R_i(t)]/c \qquad (5)$$

where $R_k(t)$ is the distance to the source from hydrophone k at time t, for $1 \le k \le N$. It can be shown that

$$R_k(t) = [v^2(t - \tau_{c,k})^2 + h^2]^{1/2} \qquad (6)$$

where $\tau_{c,k}$ is the time of CPA of the diver to hydrophone k. Suppose hydrophone n_r is the reference sensor. Then the time of CPA of the diver to the reference sensor is $\tau_{c,n_r} \equiv \tau_c$, and the time of CPA of the diver to any sensor k is related to τ_c by

$$v(\tau_{c,k} - \tau_c) = x_k - x_{n_r} \qquad (7)$$

where x_k is the x-coordinate of sensor k. Substituting (6) and (7) (with $k = i, j$) into (5) gives a model for $D_{ji}(t)$ that is a function of time t and the three motion parameters v, τ_c and h, i.e., $D_{ji}(t) \equiv D_{ji}(t; v, \tau_c, h)$.

A nonlinear least-squares (LS) estimate for each of the three motion parameters is given by

$$\{\hat{v}, \hat{\tau}_c, \hat{h}\} = \arg\min_{v,\tau_c,h} \sum_{j,i} \sum_{k=1}^{K_{ji}} [\hat{D}_{ji}(t_{ji,k}) - D_{ji}(t_{ji,k})]^2 \qquad (8)$$

where $\hat{D}_{ji}(t_{ji,k})$ is the DTOA measurement from sensor pair (j,i) at time $t_{ji,k}$, $D_{ji}(t_{ji,k})$ is the corresponding predicted value, and K_{ji} is the number of DTOA measurements from sensor pair (j,i). The DTOA measurements from a sensor pair should be taken during the time interval when the diver is passing over the sensor pair.

The nonlinear LS method was used to estimate the diver's swimming speed v, altitude h and time τ_c of CPA to the middle (reference) sensor as it passed over the two adjacent hydrophone pairs (5, 6) and (7,6) of the experimental array. The minimization in (8) was implemented in MATLAB® using the optimization function **lsqnonlin**, which required initial estimates of the three source motion parameters. The method to compute the initial estimates of v, h and τ_c, which are denoted as $\hat{v}^o$, $\hat{h}^o$ and $\hat{\tau}_c^o$ respectively, is described below.

The CPA time τ_c is the time when the diver is directly above sensor 6 (equidistant from sensors 5 and 7), i.e, when the DTOA at each sensor pair is equal. Therefore, an initial estimate of τ_c is given by

$$\hat{\tau}_c^o = \arg\min_t |\hat{D}_{56}(t) - \hat{D}_{76}(t)|. \qquad (9)$$

At time τ_c, the predicted DTOA at either sensor pair is given by $[(h^2 + d^2)^{1/2} - h]/c$, where d is the intersensor spacing, and the estimated DTOA is approximately equal to $\hat{D}_c = [\hat{D}_{56}(\hat{\tau}_c^o) + \hat{D}_{76}(\hat{\tau}_c^o)]/2$. Equating the predicted DTOA at time τ_c with the estimated value provides an initial estimate of h:

$$\hat{h}^o = \frac{d^2 - c^2 \hat{D}_c^2}{2c\hat{D}_c}. \quad (10)$$

The diver's swimming speed v is equal to the ratio of the separation distance d between the mid-points of the two sensor pairs to the time $\Delta\tau$ required for the diver to travel this distance. Denote the times when the diver is directly above the mid-points of sensor pairs (5,6) and (7,6) as τ_1 and τ_2 respectively, so that $\Delta\tau = \tau_2 - \tau_1$. Since the DTOA at either sensor pair is zero when the diver is directly above the mid-point of that sensor pair, τ_1 and τ_2 can be estimated respectively as

$$\begin{aligned} \hat{\tau}_1 &= \arg\min_t |\hat{D}_{56}(t)| \\ \hat{\tau}_2 &= \arg\min_t |\hat{D}_{76}(t)| \end{aligned} \quad (11)$$

It then follows that

$$\hat{v}^o = d/(\hat{\tau}_2 - \hat{\tau}_1). \quad (12)$$

Figure 8 shows (as circles) the DTOA measurements from the hydrophone pairs (5,6) and (7,6) for diver transit 1. For each inhaling time interval, only one DTOA measurement was taken from each hydrophone pair, which were obtained by taking a data block from the reference sensor (hydrophone 6) within the inhaling time interval and cross-correlating it with the corresponding data blocks from the other two sensors using the method of generalized cross-correlation with RTS compensation. Figure 8 also shows (as solid lines) the nonlinear LS fit of the DTOA model to the DTOA measurements from the two hydrophone pairs. The nonlinear LS estimates of v, h and τ_c are 0.5 m/s, 1.08 m and 206.245 s respectively.

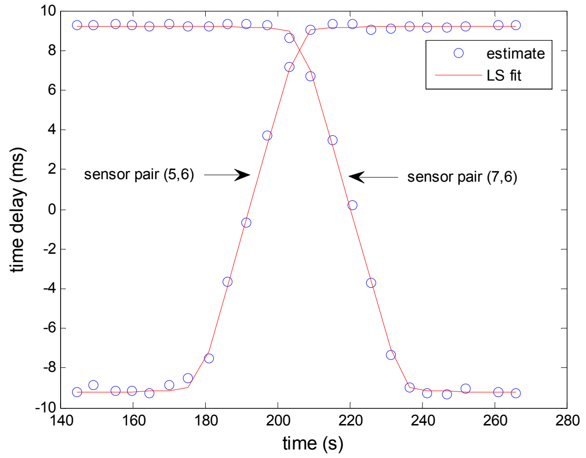


Fig. 8. DTOA measurements (circles) from hydrophone pairs (5,6) and (7,6) for diver transit 1, and nonlinear LS fit of the DTOA model (solid lines) to the DTOA measurements. For each inhaling time interval, only one DTOA measurement was taken from each hydrophone pair.

Results have also been obtained for other sets of adjacent hydrophone pairs: {(6,7), (8,7)}, {(1,2), {3,2)}, and {(2,3), (4,3)}. Table 1 shows the estimates of the diver's swimming speed and altitude when four different sets of adjacent hydrophone pairs were used. The diver's swimming speed and altitude estimates range from 0.50 to 0.54 m/s and 1.08 to 1.28 m respectively. The three motion parameters of the diver can also be estimated using a single pair of adjacent hydrophones, only that the variability of the estimates is larger. The diver's swimming speed and altitude estimates in this case range from 0.47 to 0.59 m/s and 0.60 to 2.29 m respectively.

Table 1. Diver's swimming speed and altitude estimates from four different sets of adjacent hydrophone pairs.

Sensor pairs	Speed (m/s)	Altitude (m)
(1,2) and (3,2)	0.54	1.26
(2,3) and (4,3)	0.52	1.28
(5,6) and (7,6)	0.50	1.08
(6,7) and (8,7)	0.52	1.23

CONCLUSIONS

The periodicity of a diver's acoustic signature is readily observed on the output spectrogram of a single hydrophone, and a cyclic frequency analysis of the hydrophone output signal using either DEMON or cyclostationary processing leads to the automated detection of the diver and an estimate of the diver's breathing rate. The inhaling time intervals of the diver observed at a given hydrophone can be estimated by measuring the variation with time of the integrated output energy of the hydrophone over a certain frequency range where the SNR is high. Restricting DTOA measurement using the generalized cross-correlation method to the inhaling time intervals greatly reduces the number of noisy DTOA estimates that would otherwise have occurred during the exhaling time intervals. The relative time-scaling effect which results in a loss of coherence between the signals received by a pair of hydrophones can be remedied by using the wideband cross-ambiguity function which is equivalent to wideband cross-correlation with RTS compensation. For a diver moving along and over the axis of a linear array of widely separated hydrophones at a constant speed and a constant altitude, fitting a DTOA model in a nonlinear LS sense to the DTOA measurements from two pairs of adjacent hydrophones provides estimates of the diver's swimming speed, altitude and time of CPA to the reference hydrophone. This nonlinear LS method can be generalized to estimate all five motion parameters (which specifies the trajectory) of a diver moving over a planar array of widely separated hydrophones in a straight line at constant speed and altitude. The work described in this paper can be applied to a distributed underwater acoustic sensor network for the passive detection and localization of open-circuit scuba divers in a harbor environment

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