In situ source level and source position estimates of biological transient signals produced by snapping shrimp in an underwater environment

Brian G. Ferguson and Jane L. Cleary
Maritime Operations Division, Defence Science and Technology Organisation, P.O. Box 44, Pyrmont NSW 2009, Australia

(Received 26 February 2000; accepted for publication 13 November 2000)

Biological transient signals produced by snapping shrimp are sensed underwater by a wide aperture array. The instantaneous range and bearing of the source position of each snap is estimated along with a source level equal to the peak-to-peak amplitude of the pressure impulse generated by the snap at a standard distance of 1 m from its point of origin. For a sample of 1000 snaps recorded in Sydney Harbour, the distribution of peak-to-peak sound pressure levels has a mean value of 187 dB (re 1 μPa) and an interquartile range of 185–189 dB (re 1 μPa). Plotting the Cartesian coordinates of the source positions of the biological transient signals over a period of time maps the two-dimensional spatial distribution of the local snapping shrimp population. The principal habitat is found to be geocoincident with a 120-m-long wharf, the closest point of which is 60 m from the middle of the receiving array. The passive ranging performance of the wide aperture array is evaluated by generating mechanical transient signals at selected positions along the wharf. Precise estimates of the relative times-of-arrival of the acoustic wavefronts lead to source range and bearing estimates with standard deviations of only 0.1 m and 0.005 degrees (respectively), in agreement with theoretical predictions. © 2001 Acoustical Society of America. [DOI: 10.1121/1.1339823]

PACS numbers: 43.80.Ka, 43.60.Gk [WA]

I. INTRODUCTION

High levels of ambient noise can affect the performance of high frequency sonar systems used by humans and marine mammals. Snapping shrimp are small crustaceans that produce high levels of ambient noise in those marine environments where the water is both warm (>11 °C) and shallow (<55 m deep).¹–⁵ A snapping shrimp has one enlarged claw⁶ that produces a short acoustic transient signal when snapped closed.⁷ The frequency response of the click is extremely wide-band with frequency components up to 200 kHz.²–⁴ When snapping shrimp congregate, the superposition of their sound impulses leads to a sustained background noise resembling a distinctive sizzling or crackling sound. In temperate and tropical waters, the dominant source of biological noise in shallow bays, harbours and inlets is attributed to snapping shrimp.¹–⁵

Previous observations of snapping shrimp sound ensembles have concentrated on measuring the autospectral density function of the biological noise and reporting the measurements as time-averaged noise spectra of spatially distributed impulsive sound sources.²–⁴ Recently, sound pressure source level measurements of single snaps have been measured in a controlled environment by housing a single specimen in a small cage in a test tank.⁷ The specimen was located at a standard distance of 1 m from a calibrated wide-band hydrophone.

However, an in situ measurement of the source level in open waters requires a reliable estimate of the range to the individual shrimp responsible for the snap so that the source level can be referenced to the standard distance. Knowledge of the source level is necessary for any modeling of the function of the sounds produced by snapping shrimp, since it determines the range at which the sounds have an effect. This is the case whether the sounds are used for stunning and killing prey,⁸ or territorial defense.⁹

This article uses a passive ranging technique based on wavefront curvature to estimate both the range and bearing of the source of each snapping sound recorded during a high-frequency sonar experiment in Sydney Harbour, where Alpheus euphrosyne richardsoni and Alpheus edwardsii are the dominant snapping shrimp species.⁶ The biological transient signals produced by snapping shrimp are sensed by a line array of three widely spaced hydrophones. Such a sensor configuration is commonly referred to as a wide aperture array because the sensor separation distance is considerably larger than the acoustic wavelengths that compose the received signal. Measuring the relative (or differential) times of arrival of the acoustic transient’s wavefront at each pair of adjacent sensors enables the instantaneous range and bearing of the source position of the transient to be estimated. The source range, which is equal to the radius of curvature of the wavefront, is required to calculate the attenuation of the signal in traveling from the source to the middle sensor of the array. Once the attenuation is known, the source level can be estimated. In the present experiment, the source level represents the peak-to-peak amplitude of the pressure impulse generated by a snap at a standard distance of 1 m from its point of origin. This approach enables a comparison of the peak-to-peak source levels of individual snaps recorded in harbour waters with the peak-to-peak sound pressure levels.

¹Electronic mail: brian.ferguson@dsto.defence.gov.au
II. PASSIVE RANGING WITH A WIDE APERTURE ARRAY

A. Range and bearing estimation

The wavefront curvature passive ranging technique uses a linear array of three widely separated but equally spaced sensors to estimate the range and bearing of an acoustic source. The source-sensor array geometry is shown in Fig. 1. The range $R$ and bearing $\theta$ are the polar coordinates of the source with respect to the position of the middle sensor of the array coinciding with the origin. If $d$ and $c$ denote the intersensor spacing and the is-speed of sound travel (respectively), then the range to the source from the middle sensor is given by

$$ R = \frac{2d^2 - c^2(\tau_{12}^2 + \tau_{23}^2)}{2c(\tau_{12} - \tau_{23})}, $$

(1)

where $\tau_{12}$ and $\tau_{23}$ are the time delays defined by the signal wavefront traversing the array. [Note that the (relative) time delay $\tau_{ij} = \tau_i - \tau_j$, where $\tau_i$ and $\tau_j$ are the absolute times-of-arrival of the wavefront at sensors $i$ and $j$, respectively.] Also, the bearing of the source measured at the middle sensor with respect to the array axis is given by

$$ \theta = \cos^{-1} \left[ \frac{c}{2d} (\tau_{12} + \tau_{23}) + \frac{c^2}{4Rd} (\tau_{12}^2 - \tau_{23}^2) \right]. $$

(2)

If the sound speed and sensor spacings are known, then the source range and bearing can be estimated by replacing the time delays $\tau_{12}$ and $\tau_{23}$ by their estimates in Eqs. (1) and (2).

B. Time delay estimation

The time delay is estimated by cross-correlating the outputs of a pair of sensors, $x_i(t)$ and $x_j(t)$, over an observation period of $T$. The cross-correlation function is given by

$$ r_{ij}(\tau) = \int_{-T/2}^{T/2} x_i(t-\tau)x_j(t)dt. $$

(3)

If the acoustic source of interest emits a transient signal $s(t)$, and $n_i(t)$ and $n_j(t)$ represent uncorrelated additive zero-mean noise terms, then the outputs of the two sensors can be modeled as

$$ x_i(t) = s(t) + n_i(t), $$

(4a)

$$ x_j(t) = \alpha s(t-\tau_d) + n_j(t), $$

(4b)

where $\alpha$ is an attenuation factor and $\tau_d$ is the time delay between the two sensors. Substituting Eqs. (4a) and (4b) into Eq. (3) and assuming that the observation period is infinitely long ($T \to \infty$) so that the effect of noise is reduced to zero, then the cross-correlation function becomes

$$ r_{ij}(\tau) = \alpha \int_{-\infty}^{\infty} s(t-\tau)s(t-\tau_d)dt = \alpha r_{ss}(\tau-\tau_d), $$

(5)

where $r_{ss}(\tau)$ is the autocorrelation function of $s(t)$ defined by

$$ r_{ss}(\tau) = \int_{-\infty}^{\infty} s(t)\, s(t+\tau)dt. $$

(6)

Since $r_{ss}(\tau) \leq r_{ss}(0)$, it follows from Eq. (5) that $r_{ij}(\tau)$ attains its global maximum at $\tau = \tau_d$. Thus, the time lag value that maximizes $r_{ij}(\tau)$ is an estimate of the time delay $\tau_d$.

C. Variances of range and bearing estimates

Using the far-field approximation (i.e., $R \geq 10d$), Eqs. (1) and (2) become

$$ R \equiv \frac{d^2 \sin^2 \theta}{c(\tau_{12} + \tau_{23})}, $$

(7)

$$ \theta \equiv \cos^{-1} \left[ \frac{c}{2d} (\tau_{12} + \tau_{23}) \right]. $$

(8)

The major source of error in estimating the range is the error in the time delay difference estimate, $(\tau_{12} - \tau_{23})$, in the denominator of Eq. (7). The variance of the range estimate, $\sigma_R^2$, is related to the variance of the time delay difference estimate, $\sigma_{\tau_{12} - \tau_{23}}^2$, by

$$ \sigma_R^2 \equiv c^4 \left( \frac{R}{d \sin \theta} \right)^4 \sigma_{\tau_{12} - \tau_{23}}^2, $$

(9)

or, in terms of standard deviations,

$$ \sigma_R \equiv c \left( \frac{R}{d \sin \theta} \right)^2 \sigma_{\tau_{12} - \tau_{23}}. $$

(10)

Similarly, the variance in the bearing estimate, $\sigma_\theta^2$, is related to the variance of the time delay sum estimate, $\sigma_{\tau_{12} + \tau_{23}}^2$, by
or, in terms of standard deviations

\[ \sigma_\theta = \frac{c}{2d \sin \theta} \sigma_{r_{12}+r_{23}} \]

where \( \sigma_\theta \) is in radians.

Unlike the bearing error variance \( \sigma_\theta^2 \) (which is independent of range), the range error variance \( \sigma_R^2 \) depends on the fourth power of the ratio of the source range to the half-length of the array’s effective baseline \( (d \sin \theta) \). Figure 1 shows a range-bearing error ellipse depicting the uncertainty in localizing the source position using the wavefront curvature passive ranging method. In comparison with the range estimate, the bearing estimate is much less sensitive to time delay estimation errors especially when the source is far from the array. Hence, an ellipse bounds the area of uncertainty in the source position with the elongation of the major (range) axis with respect to the minor (bearing) axis reflecting the larger variance of the range estimates when compared with the variance of the bearing estimates. [Note that close agreement between theory and experiment for the variation of range and bearing error variances with the effective half-length of the array \( (d \sin \theta) \) has been reported recently for broadband sources of continuous sound in air.]

### III. RANGE AND BEARING ESTIMATES OF MECHANICAL ACOUSTIC TRANSIENTS

A wide aperture array consisting of a line array of three calibrated hydrophones is deployed in Sydney Harbour, where high-frequency sonar experiments are conducted in very shallow water (<10 m deep). An additional (fourth) hydrophone is deployed in a direction that is broadside to the wide aperture array axis so as to resolve the left-right ambiguity problem common to line arrays. The operation of the system is controlled from the shore and the digital data acquisition system samples each sensor output at the rate of 1 million samples/s. Figure 2 is an isometric drawing of the wide aperture array where the intersensor separation distance is 9.7 m. The sensors are 1.3 m above the sea floor, which is composed of sand. At the experimental site, the water depth is 6.1 m plus the height of the tide, which varies from 0.1 to 1.9 m. For the present experiment, the measured speed of sound propagation in the underwater medium is 1520 m/s.

The passive ranging performance of the system is tested by generating mechanical transient signals underwater from a known position and using the wide aperture array to localize the source. Striking a metal tube that is attached to a wharf produces the mechanical transient signal; the tube protrudes 0.3 m below the sea surface at high tide. Each adjacent pair of sensor outputs is cross-correlated and the relative times-of-arrival of the signal estimated as the acoustic wavefront traverses the array. The cross-correlation is implemented in the frequency domain using a rectangular frequency window between 1 and 100 kHz. Each time lag increment \( (\delta \tau) \) is equal to one sampling period, that is, 1 \( \mu \)s. Figure 3(a) shows a typical example of the cross-correlation function for a mechanical transient signal. Figure 3(b) is a zoom of the cross-correlogram peak in the neighborhood of its maximum. The time delay estimate is refined by (three-point) quadratic interpolation, which is equivalent to inverse

![FIG. 2. Isometric drawing of the wide aperture array structure. The inter-element spacing of the three-hydrophone line array is 9.7 m with the sensors being 1.3 m above the sea floor.](image)

![FIG. 3. (a) The cross-correlogram of a mechanical transient signal obtained by cross correlating the outputs of sensors 1 and 2 of the wide aperture array and (b) a zoom of the cross-correlogram in the neighborhood of the peak where the time delay estimate is refined by quadratic interpolation.](image)
parabolic interpolation. Refining the time delay estimate is a two-step process:

Step 1—Determine the initial (coarse) estimate of the time delay, which is equal to the argument \( (m \delta T) \) that maximizes the sequence \( r_{ij}(k \delta T), \ 1 \leq k \leq K \).

Step 2—Calculate the refined (subsample) estimate \( (\tau_d) \) which is given by

\[
\tau_d = m \delta T - \frac{\delta T}{2} \left( \frac{r_{ij}(m \delta T + \delta T)}{r_{ij}(m \delta T + \delta T) - 2r_{ij}(m \delta T) + r_{ij}(m \delta T - \delta T)} \right)
\]

In Fig. 3(b), \( m = -3149, \ \delta T = 1 \ \mu s \) and \( \tau_d = -3148.7 \ \mu s \).

The time delay estimates for each pair of adjacent sensors are shown in Fig. 4 for a sequence of 200 mechanical transient signals generated at the first source position. The scatter in each sequence of time delay estimates is small (respectively standard deviations of 0.6 and 0.5 \( \mu s \)), implying the signal-to-noise ratio is high and the bandwidth of the mechanical transient signal is wide. Simultaneous (refined) time delay estimates (one for each pair of adjacent sensors) are substituted for \( \tau_{12} \) and \( \tau_{23} \) in Eqs. (1) and (2) to calculate (respectively) the instantaneous range and bearing of the source. The range and bearing estimates of the source position are shown in Fig. 5 for the sequence of 200 mechanical transients. The high precision of the source localization method is reflected in the small scatter of the range and bearing estimates: the standard deviations of the range and bearing estimates are 0.08 m and 0.005 degrees, respectively. [Note that if the far-field approximation is invoked, then Eqs. (7) and (8) provide range and bearing estimates to within 0.2\% of the values calculated using the exact Eqs. (1) and (2).]

The polar coordinates of each of the estimated source positions shown in Fig. 5 are transformed to Cartesian coordinates (with the middle sensor of the array as the origin) and the results presented in Fig. 6. The predicted range-bearing positional uncertainty ellipse is superimposed on the twodimensional spatial distribution of the observed acoustic source positions. The ellipse has major and minor axes equal to \( \pm 3 \sigma_R \) and \( \pm 3 \sigma_\theta \), where \( \sigma_R \) and \( \sigma_\theta \) are calculated using Eqs. (10) and (12).

Similar results are obtained for a longer sequence of

FIG. 4. Time delay estimates for a sequence of 200 mechanical transient signals generated at source position 1 (P1) using (a) sensors 1 and 2, and (b) sensors 2 and 3.

FIG. 5. (a) Range and (b) bearing estimates of the source position for the same sequence of 200 mechanical transient signals generated at source position 1 (P1).
mechanical transients at the same position, and at two other positions along the wharf. The observed and predicted standard deviations in the range and bearing estimates are shown in Fig. 7 where the experimental results match the theoretical values calculated using Eqs. (10) and (12).

Figure 8 is a plan view of the sensor–source geometry showing the mean acoustic position estimates of the three sources (P1, P2, P3) of mechanical transient signals and the position of each of the sensors that comprise the wide aperture array. The origin coincides with the position of the middle sensor of the wide aperture array. The perimeter and hatched area of the rectangle represent the naval wharf along which the three mechanical transient source positions are distributed.

**IV. RANGE AND BEARING ESTIMATES OF BIOLOGICAL ACOUSTIC TRANSIENTS**

The acoustic sensor data for the biological transient signals produced by snapping shrimp are processed in the same way as the mechanical transient signals. Only single snaps, which are both free of multipath effects and occur in isolation in the 25-ms data window, are selected for processing. Figure 9 shows the source position estimates of 1000 biological transient signals together with the source position estimates of the mechanical transients and the position of the wharf. Most of the source positions of the snapping sounds are geocoincident with the position of the naval wharf. The two-dimensional distribution of the source positions of the biological transient signals delineates the extent of the wharf.

Figure 10 is a wireframe mesh showing the spatial density of the source position estimates of the 1000 biological transients over an area 100×100 m²; each mesh cell is 1×1 m². The mesh height is proportional to the number of snaps.
per unit area over the rectangular grid. The mesh plot confirms that the principal habitat of the local snapping shrimp population is the subsurface structure of the wharf, indicating that it is conducive to snapping shrimp habitation.

Although the passive ranging method is applied here to the localization of snapping shrimp transients, it has general application to the localization of other underwater biological transient signals. The duration of the experiment was of sufficient length to enable the extent of the habitat to be localized. A longer-term experiment could provide data on diurnal and seasonal variations in the spatial distribution of the snapping shrimp colony. Passive ranging is a nonintrusive method for monitoring the underwater acoustic environment and could be a useful tool for marine park management.

V. SOURCE LEVEL ESTIMATES OF BIOLOGICAL TRANSIENTS

The peak-to-peak voltage level at the output of the middle receiver is converted to peak-to-peak source level using the calibrated receiving response of the middle hydrophone, the known gain of the receiving system and the spreading loss (calculated using the range estimate of the source.) For the present experiment, the absorption loss is ignored, as it is less than the system measurement uncertainty (±1 dB). Figure 11 shows the peak-to-peak source levels for the 1000 snaps. The median value of the source level distribution is 187 dB (re 1 μPa) with the lower quartile [~185 dB (re 1 μPa)] and the upper quartile [~189 dB (re 1 μPa)] bounding the interquartile range, which includes half the source level estimates. This result for harbour waters is in agreement with the range of peak-to-peak source levels [183–190 dB (re 1 μPa)] reported for a tank experiment in which the source levels were averaged over ten snaps from each of the 40 snapping shrimp specimens.

VI. CONCLUSIONS

Passive ranging using a wide aperture array and the wavefront curvature method provides reliable range and bearing estimates of source positions of underwater acoustic transient signals. The observed standard deviations of the range and bearing estimates of the mechanical transient source positions match the values predicted by theory. Plotting the source positions of a long sequence of snapping sounds enables snapping shrimp habitats to be localized and mapped. The in situ peak-to-peak source level measurements of the snapping sounds recorded in harbour waters agree with those reported for a controlled experiment conducted in a test tank.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the contributions of their colleagues—Doug Cato, Lionel Criswick, Chris Halliday, Kam Lo, Angus Machines, Bill Martin, Anthony Quach, Mark Readhead, John Shaw, Gary Speechley, Ross Susic, Neil Tavener and Ranjit Thuraisingham. The authors also appreciate the support and assistance provided during the experiment by the Royal Australian Navy’s Clearance Diving Team One (HMAS Waterhen) and LCDR Sue Smith RAN (Executive Officer, HMAS Penguin). The Royal Australian Navy Missile Maintenance Establishment—ARMLO.

FIG. 9. Similar to Fig. 8 but with the inclusion of the estimated source positions of 1000 biological transient signals.

FIG. 10. Spatial distribution of the source position density of the biological transient signals. The positions of the three sensors that comprise the wide aperture array are also shown.

FIG. 11. Peak-to-peak source levels for 1000 biological transient signals.
expertly machined the mechanical subassemblies of the array structure. Shane Ahyong of the Marine Invertebrate Department of the Australian Museum provided information on the snapping shrimp species in Sydney Harbour.