Hossain and Hossen introduce the impact of dispersion coefficient on cross-correlation based population estimation technique of fish and mammals.

One fish, two fish

Who should read this paper?
Those involved in acoustic signal processing research, marine biological research, and commercial or occasional fishery management should read this paper.

This paper introduces the impact of dispersion coefficient, the main factor of the distance dependent attenuation, on cross-correlation based population estimation technique of fish and mammals. Cross-correlation based passive fishery survey technique was introduced as an alternative to conventional ones. The authors gradually increased the value of dispersion coefficient and compared the results with no dispersion case results. They found that with the increase of dispersion factor, i.e., dispersion loss in the medium, a significant amount of deviation occurred from the actual fishery quantity to the estimated. They have considered chirp-generating species of fish and mammals during the simulations.

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IMPACT OF DISPERSION COEFFICIENT ON CROSS-CORRELATION BASED POPULATION ESTIMATION TECHNIQUE OF FISH AND MAMMALS

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ABSTRACT

Generally, passive monitoring is used to survey soniferous fish and mammals, which are difficult to monitor using conventional visual methods. This type of monitoring has the benefit of being a non-invasive and non-destructive observational tool, and offers unbiased data on the position and movement of aquatic animals. With an aim to overcome the limitations of conventional fishery monitoring techniques, a cross-correlation based passive acoustic technique was proposed as an alternative. Using this technique, the receiving of fish sound is sometimes difficult due to the distance-dependent attenuations, i.e., in the medium, loss of signal strength with increasing distance. In this study, we have analyzed the impact of dispersion coefficient, the main factor of the distance dependent attenuation, on cross-correlation based population estimation technique of fish and mammals. We found that with the increase of dispersion factor, i.e., dispersion loss in the medium, a significant amount of deviation occurred from actual fishery quantity to the estimated. Chirp sound, which is commonly generated by damselfish (Dascyllus aruanus), was considered in this study to accomplish the simulations.

KEYWORDS

Population estimation; Chirps; Dispersion coefficient; Cross-correlation function; Acoustic sensors

INTRODUCTION

As a residence of myriad organisms dwelling in different ecosystems, the ocean is a tremendous diversity and species-abundant place, where fish and mammals are the key elements. But, inauspiciously, the ocean dwellers are struggling for their existence. According to a report of World Wildlife Fund, the population size of fish, marine mammals, birds, and reptiles had fallen 49% between 1970 and 2012; for fish alone, the decline was 50% [Doyle, 2015]. This alarming report reminds us of the importance of proper management and conservation of fish and mammals. An efficient monitoring of populations and communities is the precondition of ecosystem-based management in marine areas. But it is hard to estimate the exact population of fish and mammals in any particular area of the ocean, where the dynamics of their population and the harsh condition of the ocean represent the main difficulties in obtaining accurate data.
Many investigations have been conducted for estimating fishery population. These approaches can be classified into two, i.e., non-acoustic and acoustic techniques [Hossain et al., 2019]. Major non-acoustic techniques are removal method [Pollock, 1991], visual sampling techniques [Hankin and Reeves, 1988], prediction-based macro ecological theory [Jennings and Blanchard, 2004], etc., of which most suffer from several problems, e.g., time consuming nature, poor accuracy, mostly human interaction, costly mechanical instruments, and so on. Therefore, acoustic techniques became popular, which are classified into two categories, i.e., active and passive acoustic techniques [Hossain et al., 2019]. Some conventional active acoustic techniques are echo integration technique [MacLennan, 1990], dual-frequency identification sonar technique [Boswell et al., 2008], dual-beam transducer technique [Ehrenberg, 1974], etc., which comprise some common limitations, e.g., requirement of larger number of fish and mammals for proper estimation, requirement of costly electronic instruments and monitoring, protocol complexity, etc.

Nowadays, emphasis is put on passive acoustic monitoring of fishery populations, which is an emerging field in fisheries surveys. It takes advantage of the fact that many species of fish and mammals produce sounds naturally and therefore possess natural acoustic tags. Generally, the passive acoustic technique utilizes low-frequency (<10 kHz) acoustic sensors to detect and monitor natural sound production by fish and mammals, which is typically associated with feeding, aggressive encounters, courtship, or spawning behaviour [Luczkovich et al., 2008]. There are more than 700 species known to produce sounds from at least 30 families and many more soniferous fish and mammals have yet to be recorded [Rountree et al., 2006]. It provides some benefits over other methods of fishery population estimation. First, it has the advantage of non-optically observing fish activity and distribution. That is, it can be utilized to find and monitor fish and mammals that produce sound. Second, as a non-invasive and non-destructive observational tool, it provides unbiased data on the position and movement of aquatic animals [Putland et al., 2018]. Third, it provides the capability of continuous or long-term monitoring as well as remote monitoring. Such long-term monitoring can provide important information on daily and seasonal activity patterns of fish and mammals [Luczkovich et al., 2008].

However, passive acoustics has been used for over 50 years in fish biology and fishery monitoring and is being used regularly today to determine habitat use, delineate and monitor spawning areas, and study the behaviour of fish and mammals [Hawkins, 1986; Tickler et al., 2019]. Cross-correlation based population estimation technique of fish and mammals was also proposed as a passive acoustic monitoring technique [Hossain et al., 2018; Rana et al., 2014; Hossain and Hossen, 2018; 2019]. This statistics-based technique can resolve several drawbacks of conventional techniques like complexity, reliance on human interaction, time consuming nature of estimation, sensitivity, high cost, etc. In the past, the researchers of this technique considered no path loss to accomplish their simulated estimation. But, in practice, path loss occurs due to the distance-
dependent attenuations. In this paper, our main focus was to pursue this estimation technique considering the impact of dispersion coefficient, which is the main factor of the distance-dependent attenuation. This study is important because in real-time estimation dispersion has a practical impact and a simulated analysis of this impact can give an assumption during the practical implementation of this technique. In this study, we have used MATLAB software as our simulation tool and considered chirp generating fish and mammals, e.g., damselfish (*Dascyllus aruanus*), humpback whales (*Megaptera novaeangliae*), dugongs (*Dugong dugon*), etc.

CROSS-CORRELATION BASED POPULATION ESTIMATION TECHNIQUE OF FISH AND MAMMALS: A REVIEW

Passive acoustics has a long history in fish biology, but, recently, it has been applied to fisheries and their management [Tickler et al., 2019]. Generally, the sounds produced by soniferous fish and mammals are commonly comprised of low-frequency pulses, which vary in duration, number, and repetition rate [Myrberg, 1978]. Different types of sounds produced by different fish and mammals have their own characteristics. These acoustic behaviours are considered in cross-correlation based estimation technique, which is also a passive acoustic technique [Putland et al., 2018]. In this technique, a particular volume is considered, where acoustic signals produced by soniferous fish and mammals are used as a consequence of their acoustic behaviours. Transmitted acoustic signals from *N* fish and mammals are received by two [Hossain et al., 2018; Rana et al., 2014], three [Hossain and Hossen, 2018; 2019], or more acoustic sensors at different delays and summed at each sensor location forming composite signals. However, in this review, we have considered a two sensors case of cross-correlation based passive monitoring technique [Hossain et al., 2018; Rana et al., 2014].

The formulation of cross-correlation of fish sound is like the formulation of cross-correlation of Gaussian signal [Anower, 2011], which are the starting materials and method to estimate the population size of marine fish and mammals. All the transmitted signals are received by the acoustic sensors and recorded in the associated computer in which cross-correlation is executed. Transmission and reception of signals are performed for a time frame, called “signal length.” Soniferous fish and mammals are considered as the sources of acoustic signals and *N* fish and mammals are distributed over the volume of a large sphere, the centre of which lies halfway between the acoustic sensors. A distribution of fish and mammals (simulation) is shown in Figure 1(a). A constant propagation velocity is considered, called the sound velocity, *S*<sub>p</sub>, in the medium.

Two acoustic sensors, *H*<sub>1</sub>, *H*<sub>2</sub>, and a fish (acoustic source), *N*<sub>1</sub>, are considered as shown in Figure 1(b). The acoustic sensors *H*<sub>1</sub>, *H*<sub>2</sub> and the fish *N*<sub>1</sub> are located at (*x*<sub>1</sub>, *y*<sub>1</sub>, *z*<sub>1</sub>), (*x*<sub>2</sub>, *y*<sub>2</sub>, *z*<sub>2</sub>), and (*x*<sub>3</sub>, *y*<sub>3</sub>, *z*<sub>3</sub>), respectively. If the distance between the two acoustic sensors is *d*<sub>DBS</sub> then:

\[
d_{\text{DBS}} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}
\] (1)
Figure 1: (a) A distribution of fish and mammals, where the two pluses (+) indicate the acoustic sensors and (b) from a distribution of fish and mammals in 3D spaces, a fish N1 is considered, where H1 and H2 are the acoustic sensors.
A signal coming from $N_1$ is $S_1(t)$, which is finite in length. As such, the signals received by $H_1$ and $H_2$ are correspondingly:

\begin{align}
S_{r_11}(t) &= \alpha_{11}S_1(t - \tau_{11}) \\
S_{r_12}(t) &= \alpha_{12}S_1(t - \tau_{12})
\end{align}

(2)

(3)

where, $\tau_{11} = d_1/S_p$ and $\tau_{12} = d_2/S_p$ are the corresponding time delays for the signal to reach each acoustic sensor and $\alpha_{11}$ and $\alpha_{12}$ are the attenuations due to absorption.

Assuming $\tau_1$ is the time shift in the cross-correlation and then the cross-correlation function (CCF) is:

\begin{equation}
C_1(\tau) = \int_{-\infty}^{\infty} S_{r_11}(t)S_{r_12}(t - \tau_1)d\tau
\end{equation}

(4)

It takes the form of a delta function as it is a cross-correlation of two signals, where one signal is fundamentally the delayed copy of another.

To find the CCF for N fish and mammals, we have to sum the total signals received by the acoustic sensors from each of the fish or mammals. So, the total signals $S_{r_{f_1}}$ at sensor $H_1$ is calculated by the following formula:

\begin{equation}
S_{r_{f_1}} = \sum_{j=1}^{N} \alpha_{j1}S_j(t - \tau_{j1})
\end{equation}

(5)

While the total signals at sensor $H_2$ is $S_{r_{f_2}}$ and can be calculated as follows:

\begin{equation}
S_{r_{f_2}} = \sum_{j=1}^{N} \alpha_{j2}S_j(t - \tau_{j2})
\end{equation}

(6)

Assuming $\tau = d_{obs}/S_p$ is the time shift in the cross-correlation. Hence, the final CCF between the signals at the acoustic sensors is:

\begin{equation}
C(\tau) = \int_{-\infty}^{\infty} S_{r_{f_1}}(t)S_{r_{f_2}}(t - \tau)d\tau
\end{equation}

(7)

Bin, $b$, in the CCF (as shown in Figure 2) is defined as a place occupied by a delta inside a space of a width of twice the distance between acoustic sensors and that place is determined by the delay difference of the signals coming to the acoustic sensors [Anower, 2011]. The deltas of equal delay differences are placed in that particular bin. Number of bins, $b$, is achieved from the sampling rate, $S_R$, distance between sensors, $d_{obs}$, and speed of signal propagation, $S_p$, which all are predefined and described in [Anower, 2011].

\begin{equation}
b = \frac{2 \times d_{obs} \times S_R}{S_p} - 1
\end{equation}

(8)

Direct calculation of these estimation parameters using statistical expression is convoluted. Hence, a cross-correlation problem is reframed to a probability problem using the renowned occupancy problem that follows the binomial probability distribution, where the parameters are the population size of fish and mammals.
mammals $N$ and $1/b$ [Anower, 2011]. By reframing, we can find the estimation parameter, i.e., ratio of standard deviation to mean, $R$, as in Anower [2011].

$$R = \frac{\sigma}{\mu} = \sqrt{\frac{N \times \frac{1}{b} \times (1 - \frac{1}{b})}{\frac{N}{b}}} = \sqrt{\frac{b - 1}{N}}$$

(9)

where $\mu$ is the mean of the CCF and $\sigma$ is the standard deviation of the CCF.

We have considered $R$ as the estimation parameter because it is independent of signal strength since it is the ratio of two parameters [Anower, 2011].

A block diagram representation of the entire process is shown in Figure 3.

However, due to the movement of fish and mammals, the Doppler effect may have occurred that was not considered in this technique. Due to the Doppler effect, there will be a slight variation in the propagation wavelength and, thus, in propagation delay, which can affect the placing of balls in the bins of the cross-correlation process and might lead to fractional-sample delays being created [Anower, 2011]. However, the impact of fractional samples has no significant effect on estimation.

METHOD AND PARAMETERS

Chirp generating fish and mammals can transmit signals of equal power but the received powers are different due to the distance-dependent attenuations, which also depend on the dispersion coefficient, $k$. To show the impact of it on cross-correlation based population estimation technique of fish and mammals, a similar setup discussed in the previous section is employed to perform the simulations, i.e., two spatially separated sensors are placed somewhere in the middle of a sphere inside a cube such that the diameter of the sphere is equal to the dimension of the cube and the sphere is filled with fish and mammals. The chirp signals emitted from the fish and mammals are collected by the acoustic sensors. By cross-correlating these two signals at the acoustic sensors, the CCF is obtained. Using this CCF, the estimation tool, i.e., the ratio of the standard deviation to the mean of the CCF, is obtained, which is a rectangular pulse over the space between the acoustic sensors. Then it becomes easy to determine the mean and standard deviation of this CCF and, therefore, the ratio, $R$, as the sampling rate and $dBBS$ are known. In this study, we mainly have analyzed the performance of cross-correlation based passive monitoring technique by means of dispersion coefficient. We gradually increased the value of dispersion coefficient and obtained the results by simulation. Therefore, the methodology is similar as discussed in the previous section.
We have considered a uniform random distribution of fish and mammals during the simulation. To ease the simulation, a negligible amount of power difference among the acoustic pulses transmitted by each fish or mammal was considered during their transmitting times.

We have used MATLAB software as our programming tool. The parameters used in our simulations are given in Table 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension of the sphere</td>
<td>2000 m</td>
</tr>
<tr>
<td>Distance between the equidistant sensors, $d_{\text{DIS}}$</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Speed of propagation, $S_p$</td>
<td>1500 m/s</td>
</tr>
<tr>
<td>Sampling rate, $S_R$</td>
<td>60 kSa/s</td>
</tr>
<tr>
<td>Absorption coefficient, $a$</td>
<td>1 dBM$^{-1}$</td>
</tr>
<tr>
<td>Number of bins, $b$</td>
<td>39</td>
</tr>
<tr>
<td>Number of iterations averaged</td>
<td>500</td>
</tr>
<tr>
<td>Considered fish distribution</td>
<td>Uniform random distribution</td>
</tr>
</tbody>
</table>

We have considered a 26.02 dB signal-to-noise ratio to accomplish the simulation [Hossain and Hossen, 2019]. The major functions used in simulation are xcorr, rand, chirp, std, disper, etc. The occurrence of multipath interference was not considered and the delay was taken to be integers in all cases in the simulation.

IMPACT OF DISPERSION COEFFICIENT

In this section, the effect of dispersion coefficient, the main factor of the distance dependent attenuation is discussed. We have considered chirp generating fish and mammals and a gradual increasing of dispersion coefficient strategy to accomplish the simulation.

mammal species like dugongs (*Dugong dugon*) [Ichikawa et al., 2011], etc., can produce chirp-like sound. From a sound analysis of *Plectroglyphidodon lacrymatus* and *Dascyllus aruanus* species of damselfish, it was found that their generated chirps consisted of trains of 12-42 short pulses of three to six cycles, with durations varying from 0.6 to 1.27 ms; peak frequency varied between 3,400 to 4,100 Hz [Parmentier et al., 2006]. However, a chirp signal is a swept-frequency signal, which has a time varying frequency. Such a signal can be expressed as Hossain et al. [2018]; Rana et al. [2014]; Hossain and Hossen [2018]; and Hossain et al. [2019]:

$$X(t) = A \cos \left[2\pi \left( \frac{(f_2 - f_1)t^2}{2d} + f_1t \right) \right] + P$$

(10)

**Chirp**

From diverse frequencies and names of fish sounds, e.g., chirps, grunts, growls, pops, hoots, clicks, whistles, etc., chirp is considered in this study, which is commonly generated by damselfish [Amorim, 2006]. Likewise, some species of whale including humpback whales (*Megaptera novaeangliae*) [Winn et al., 1979], some dolphin species, including bottlenose dolphins [Caldwell and Caldwell, 1970], some
where, \( f_1 \) is the starting frequency in Hz, \( f_2 \) is the ending frequency in Hz, \( d \) is the duration in second, \( P \) is the starting phase, and \( A \) is the amplitude [Hossain et al. [2018]; Rana et al. [2014]; Hossain and Hossen [2018]].

**Population Estimation of Fish and Mammals Considering Different Dispersion Coefficients**

The signals transmitted by the fish and mammals are of equal strength. However, the power received by the sensors is not equal because there will be loss in the path due to distance-dependent attenuation. This loss can be determined by the effect of dispersion coefficient, \( k \), as attenuation is used for underwater sound [Anower, 2011]:

\[
L_p \propto d^{-k} \tag{11}
\]

where \( L_p \) is the path loss and \( d \) is the distance.

To investigate the impact of dispersion coefficient in the simulation, we have increased the value of \( k \) gradually. At first, we have estimated the \( R \) of CCF considering no path loss, i.e., \( k = 0 \). Figure 4 represents the deviation between theoretical and simulated \( R \) of CCF with respect to fish and mammals. We have considered this simulated result to compare it with the results for the increasing values of \( k \). However, we have gradually increased the value of \( k \), i.e., \( k = 0.5, 1, 1.5, \) and \( 2 \). The corresponding results are illustrated in Figure 5. Actually, in Figure 5, a comparison between estimation with no path loss and estimation with gradually increasing the path loss is shown.

In Figure 4, the blue line corresponds to the theoretical results and the circles with the red line correspond to the simulated results for \( k = 0 \). On the other hand, in Figure 5 (a), the circles with the red line correspond to the simulated results for \( k = 0 \), and the stars with the blue line correspond to the simulated results for \( k = 0.5 \). In Figure 5 (b), the circles with the red line correspond to the simulated results for \( k = 0 \) and the stars with the green line correspond to the simulated results for \( k = 1 \). In Figure 5 (c), the circles with the red line correspond to the simulated results for \( k = 0 \) and the stars with the purple line correspond to the simulated results for \( k = 1.5 \). In Figure 5 (d), the circles with the red line correspond to the simulated results for \( k = 0 \) and the stars with the dark-blue line correspond to the simulated results for \( k = 2 \).

From Figure 4, we can see that the theoretical results are close to the simulated results. With increase of the values of \( k \), the simulated results shown in Figure 5 are degraded compared to simulated results in Figure 4. These results will assist future researchers during investigations of the applied fields of this technique with different types of dispersion coefficient values. Moreover, it will help researchers during the practical implementation of this technique. Table 2 represents a comparison among different results achieved for different values of \( k \).

**DISCUSSION**

Dispersion loss, also known as spreading loss, is due to the geometrical dispersion of the signal in the underwater medium. When an acoustic signal propagates further away from its
Figure 4: Number of fish and mammals, $N$ vs. $R$ of CCF for $k=0$.

Figure 5: Number of fish and mammals, $N$ vs. $R$ of CCF, (a) comparison between $k = 0$ and $k = 0.5$, (b) comparison between $k = 0$ and $k = 1$, (c) comparison between $k = 0$ and $k = 1.5$, and (d) comparison between $k = 0$ and $k = 2$. 
Table 2: Comparison among $R$ of CCF for different values of $k$.

<table>
<thead>
<tr>
<th>Actual Number of Fish and Mammals</th>
<th>$R$ from Theory</th>
<th>$R$ from Simulation for $k=0$</th>
<th>$R$ from Simulation for $k=0.5$</th>
<th>$R$ from Simulation for $k=1$</th>
<th>$R$ from Simulation for $k=1.5$</th>
<th>$R$ from Simulation for $k=2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.949</td>
<td>1.798</td>
<td>1.674</td>
<td>2.462</td>
<td>1.30</td>
<td>2.974</td>
</tr>
<tr>
<td>20</td>
<td>1.378</td>
<td>1.305</td>
<td>1.205</td>
<td>1.092</td>
<td>0.891</td>
<td>0.806</td>
</tr>
<tr>
<td>30</td>
<td>1.125</td>
<td>1.168</td>
<td>1.036</td>
<td>1.317</td>
<td>0.789</td>
<td>0.628</td>
</tr>
<tr>
<td>40</td>
<td>0.975</td>
<td>0.925</td>
<td>1.063</td>
<td>0.860</td>
<td>1.338</td>
<td>0.571</td>
</tr>
<tr>
<td>50</td>
<td>0.872</td>
<td>0.830</td>
<td>0.813</td>
<td>0.776</td>
<td>0.667</td>
<td>0.608</td>
</tr>
<tr>
<td>60</td>
<td>0.796</td>
<td>0.814</td>
<td>0.752</td>
<td>0.817</td>
<td>1.079</td>
<td>0.496</td>
</tr>
<tr>
<td>70</td>
<td>0.737</td>
<td>0.718</td>
<td>0.677</td>
<td>0.801</td>
<td>0.591</td>
<td>0.436</td>
</tr>
<tr>
<td>80</td>
<td>0.689</td>
<td>0.664</td>
<td>0.651</td>
<td>0.607</td>
<td>0.542</td>
<td>0.450</td>
</tr>
<tr>
<td>90</td>
<td>0.649</td>
<td>0.636</td>
<td>0.678</td>
<td>0.603</td>
<td>0.785</td>
<td>0.393</td>
</tr>
<tr>
<td>100</td>
<td>0.616</td>
<td>0.603</td>
<td>0.590</td>
<td>0.645</td>
<td>0.511</td>
<td>0.355</td>
</tr>
</tbody>
</table>

Table 2: Comparison among $R$ of CCF for different values of $k$. 
source, the front of the wave occupies an ever-increasing surface area. Hence, the energy per unit surface area, i.e., the energy flow, consistently decreases. For a spherical wave generated by a point source, the dispersion loss is proportional to the square of the distance whereas, for a cylindrical wave, the loss is proportional only to the distance. It is clear that if the dispersion coefficient, \( k = 0 \) then the simulated lines maintain the same shape and are very close to theoretical population estimation. But, because of dispersion loss in the medium, there is much deviation of the simulated lines from the theoretical line, which results in a much deviated quantity from the actual quantity. And this deviation increases with the increase of the dispersion factor, \( k \). Table 2 shows the values of \( R \) of CCF for different dispersion coefficients, \( k \).

From Table 2, we find that for 100 fish and mammals, \( R = 0.616, 0.603, 0.590, 0.645, 0.511, \) and 0.355, consecutively for \( k = 0, 0.5, 1, 1.5, \) and 2. The corresponding estimated number of fish and mammals, \( N_{\text{estimated}} = 104.51, 109.11, 91.26, 145.6, \) and 301.88. Therefore, we can say that with the increase of dispersion factor, i.e., dispersion loss in the medium, the deviation from actual population to practical population increases. However, our work has some limitations, e.g., negligence of multipath interference, assuming the delays to be integer, consideration of a negligible amount of power difference among the fish sounds during transmitting time, and consideration of acoustic sensors to be laid at the middle of the estimation area.

CONCLUSION

During practical implementation, cross-correlation based passive acoustic technique can face path loss due to the distance-dependent attenuations. Dispersion coefficient is the main factor of the distance dependent attenuation. In this paper, we have analyzed the impact of dispersion coefficient on this technique. We have found that with the increase of dispersion factor, i.e., dispersion loss in the medium, the deviation from actual population size to practical population size of fish and mammals increases considerably. This finding will assist the practical implementation of this technique significantly. Research is underway on implementation of this technique with Internet of Things based systems for more convenient data transmission. However, the impact of multipath and various types of fish sounds on this technique can be an attractive field for future research.

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