Error calculation in cross-correlation based population estimation technique of fish and mammals

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1. Introduction

Population size estimation of fish and mammals is a primarily important topic in conservation of ecology and management, which can say acoustically sensitive times and areas to be prioritized. Nowadays, passive acoustic monitoring is increasingly used to locate soniferous fish and mammals [1], which are problematic to monitor using conventional visual techniques. Unlike underwater diver surveys [2] or mark recapture techniques [3], it has the advantage of being a non-invasive and non-destructive monitoring tool. In underwater environment, sound can propagate long distances in all directions without losing substantial energy [4]. However, many fish sounds are species specific and repetitive that allows passive acoustic recordings to be used to identify their population size and behavior [5]. Generally, acoustic monitoring uses the mathematics of acoustic propagation and parabolic geometry to determine source positions [5].

In order to overcome the major drawbacks of conventional fishery monitoring methods, a straight forward, cross-correlation based passive acoustic technique was proposed as an alternative [6–8]. In this technique, the authors utilized cross-correlation and occupancy problem, a follower of binomial probability distribution, to reduce the complexity [6]. The method was investigated for two [6,7] and three acoustic sensors [8], which were the receiving tools of fish sounds.

Calculation of estimation error is an important task for this technique. The difference between an actual quantity and its estimated quantity is called error and like other estimation techniques. In the proposed technique, error is also involves. Two different approaches are utilized for calculating estimation error: true error and statistical error calculations. Since cross-correlation based passive monitoring technique contains distinct statistical properties, the statistical error is appropriate to evaluate its accuracy. In addition, the coefficient of variance (CV) [9] is the statistical error measurement parameter in this technique, where the lower value of the CV provides the better accuracy of the estimation [9]. Here, CV is a probabilistic and statistical error tool. It is defined by the ratio of the standard deviation to the mean of a probability distribution.

In this study, we considered both two and three acoustic sensors cases to calculate the statistical errors and to compare

them. We also considered chirp sound, which is commonly generated by damselfish (*Dascyllus aruanus*), humpback whales (*Megaptera novaeangliae*), dugongs (*Dugong dugon*), etc., species [10] for simulation purposes. We calculated the CV from theory at first and then from simulation. To investigate the change of CV with respect to the increasing number of acoustic sensors is the main goal of this research. We used MATLAB as our simulation tool.

2. Review on cross-correlation based population estimation technique of fish and mammals

Cross-correlation based passive monitoring technique relies on different types of sounds produced by different fish and mammals, which have their own characteristics [6,10]. In this technique, a volume is considered where vocalizing fish and mammals produce acoustic signals as a consequence of their acoustic activities. Transmitted acoustic signals from N fish and mammals are received by two acoustic sensors at different delay differences and summed at each sensor location forming composite signals.

These two composite signals are then cross-correlated to formulate cross-correlation function (CCF) that results a series of delta functions stated in [9,10]. Such an acquisition of CCF is shown below for 100 fish and mammals.

Bins, b in the CCF (as shown in Fig. 1) is defined as a place occupied by a delta inside a space of a width twice the distance between acoustic sensors and that place is determined by the delay difference of the signals coming to the acoustic sensors [6,7]. 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_{DBS} , and speed of signal propagation, S_P , which all are predefined as described in [9,10].

$$b = \frac{2 \times d_{DBS} \times S_R}{S_P} - 1 \quad (1)$$

Direct calculation from statistical expression is convoluted. Hence, cross-correlation problem is reframed to a probability problem using the renowned occupancy problem that follows the binomial probability distribution, where the parameters are population size of fish and mammals, N and $1/b$ [10]. By reframing, we can find the estimation parameter, i.e., ratio of standard deviation to mean, R as [9,10]:

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Fig. 1 Bins, b in the cross-correlation process.

$$R = \frac{\sigma}{\mu} = \frac{\sqrt{N \times \frac{1}{b} \times \left(1 - \frac{1}{b}\right)}}{N/b} = \sqrt{\frac{b-1}{N}}, \quad (2)$$

where σ is the standard deviation of CCF and μ is the mean of CCF.

Thus, from Eq. (2), we can calculate N since we know b and R or μ can be calculated from CCF.

Similarly, for three acoustic sensors, two types of topologies are possible, i.e., acoustic sensors in line shape (ASL) and acoustic sensors in triangular shape (AST) [8].

For the ASL case, the final ratio of the standard deviation to the mean will be found from the average of R_{12} and R_{23} [8]. Where, R_{12} is the R for sensors 1 and 2, i.e., H_1 and H_2 as shown in Fig. 2(b), R_{23} is the R for sensors 2 and 3, i.e., H_2 and H_3 as shown in Fig. 2(c).

$$R_{\text{Average}}^{2\text{CCF}} = \frac{R_{12} + R_{23}}{2} \quad (3)$$

For the AST case, the final ratio of standard deviation to the mean is obtained from the average of R_{12} , R_{23} , and R_{31} [8].

$$R_{\text{Average}}^{3\text{CCF}} = \frac{R_{12} + R_{23} + R_{31}}{3} \quad (4)$$

Block diagram representation of the entire process is shown in Fig. 2. It is important to know that R is chosen as estimation parameter because it is independent to signal strength [9,10]. However, significant limitations of cross-correlation based technique are consideration of delays to be integers and sensors to be lied in the middle of the estimation area, which are trying to mitigate.

3. Investigation on error calculation

A theoretical and simulated calculation procedure of CV is illustrated in this section. For comparison purposes, we considered estimation with two and three acoustic sensors and calculated CV with respect to those. We also considered chirp generating species to accomplish the simulation. A sound analysis of *Plectrogliphidodon lacrymatus* and *Dascyllus aruanus* species of damselfish (family pomacentridae) demonstrated that their generated chirps consisted of trains of 12–42 short pulses of three to six cycles, with a durations from 0.6 to 1.27 ms; and the peak frequency varied from 3,400 to 4,100 Hz illustrated in [10].

Fig. 2 Block diagram representation of the process to obtain R of CCF, (a) two acoustic sensors case, (b) acoustic sensors in line shape (ASL case) and (c) acoustic sensors in triangular shape (AST case).

a. Statistical Error (CV) Calculation from Theory

As we know that CV is the key parameter to achieve statistical error, a theoretical calculation procedure of CV is illustrated in this subsection. CV is defined as the ratio of standard deviation to the mean of the estimated number of fish and mammals, which is taken from several estimations. Here, CV is independent of number of fish and mammals, N and depends only on number of bins, b , expressed as follow [9]:

$$CV_1^{1CCF} = \frac{\sigma_1^{1CCF}(N_{est})}{\mu_1^{1CCF}(N_{est})} = \sqrt{\frac{2}{(b-1)}} \approx \sqrt{\frac{2}{b}} \quad (5)$$

Equation (5) is found from single iteration for single CCF, where two acoustic sensors are used that results single R .

Now, CV_1^{1CCF} after n th iterations is

$$CV_n^{1CCF} = \frac{\sigma_n^{1CCF}(N_{est})}{\mu_n^{1CCF}(N_{est})} = \sqrt{\frac{2}{(b-1)n}} \approx \sqrt{\frac{2}{bn}} \quad (6)$$

In three acoustic sensors of ASL case, two CCFs are used for estimation and estimation parameter, $R_{Average}^{2CCF}$ is the average of R_{12} and R_{23} , obtained from the two CCFs, which is analogous to two iterations, so the standard deviation, σ_1^{1CCF} of the estimated number of fish and mammals and thus the σ_1^{1CCF} are reduced by $1/\sqrt{2}$ [9]. Therefore, in three acoustic sensors ASL case, CV_1^{2CCF} for single iteration can be expressed as:

$$\begin{aligned} CV_1^{2CCF} &= \frac{\sigma_1^{2CCF}(N_{est})}{\mu_1^{2CCF}(N_{est})} = \frac{CV_1^{1CCF}}{\sqrt{2}} \\ &= \frac{\sqrt{2}}{\sqrt{2} * \sqrt{(b-1)}} \approx \sqrt{\frac{1}{b}} \end{aligned} \quad (7)$$

So, CV_1^{2CCF} after n th iteration is:

$$\begin{aligned} CV_n^{2CCF} &= \frac{\sigma_n^{2CCF}(N_{est})}{\mu_n^{2CCF}(N_{est})} = \frac{CV_n^{1CCF}}{\sqrt{2}} \\ &= \frac{\sqrt{2}}{\sqrt{2} * \sqrt{(b-1)n}} \approx \sqrt{\frac{1}{bn}} \end{aligned} \quad (8)$$

However, for three acoustic sensors AST case, estimation parameter, $R_{Average}^{3CCF}$ is the average of R_{12} , R_{23} , and R_{31} , obtained from the three CCFs, which is analogous to three iterations [9]. Hence, in three acoustic sensors AST case, CV_1^{3CCF} for single iteration can be expressed as:

$$\begin{aligned} CV_1^{3CCF} &= \frac{\sigma_1^{3CCF}(N_{est})}{\mu_1^{3CCF}(N_{est})} = \frac{CV_1^{1CCF}}{\sqrt{3}} \\ &= \frac{\sqrt{2}}{\sqrt{3} * \sqrt{(b-1)}} \approx \sqrt{\frac{2}{3b}} \end{aligned} \quad (9)$$

Now, CV_1^{3CCF} after n th iteration is:

$$\begin{aligned} CV_n^{3CCF} &= \frac{\sigma_n^{3CCF}(N_{est})}{\mu_n^{3CCF}(N_{est})} = \frac{CV_n^{1CCF}}{\sqrt{3}} \\ &= \frac{\sqrt{2}}{\sqrt{3} * \sqrt{(b-1)n}} \approx \sqrt{\frac{2}{3bn}} \end{aligned} \quad (10)$$

b. Statistical Error (CV) Calculation from Simulation

Simulated results are executed in this subsection. CV with respect to number of fish and mammals is plotted in Figs. 3(a) and 3(b) in order to verify the relationship between CV and b . We considered both two and three acoustic sensors based estimation to show a comparison between them in term of CV. In Fig. 3, the solid lines represent the theoretical results and the circles, stars and rectangles represent the simulated results. The results are obtained after averaging 500 iterations. We considered the values as: $d_{DBS} = 0.5$ m and $S_R = 60$

(a)

(b)

Fig. 3 Number of fish and mammals vs. CV for two sensors, three sensors ASL case and three sensors AST case, (a) $b = 39$ and (b) $b = 59$.

kSa/s for $b = 39$ and $d_{DBS} = 1.0$ m and $S_R = 45$ kSa/s for $b = 59$.

In Fig. 3, the green lines indicate the theoretical result and the green rectangles represents the simulated results for two acoustic sensors case; the red lines indicate the theoretical result and the red stars represents the simulated results for ASL case; and the blue lines represent the theoretical results and the blue circles represents the simulated results for AST case. Figure 3(a) is simulated for 39 bins and Fig. 3(b) is for 59 bins. We can see that CV is decreasing with the increasing of b . We also see that the CV is decreasing with the increasing of CCFs, i.e., CV_{500}^{2CCF} is lower than CV_{500}^{1CCF} and CV_{500}^{3CCF} is lower than CV_{500}^{2CCF} . This indicates the accuracy of estimation with three acoustic sensors ASL case is higher than estimation with two acoustic sensors case but lower than three acoustic sensors AST case since we know that the lower the CV value the higher the accuracy. With the lower value of CV the difference between theoretical R and simulated R will be decreased. In cross-correlation based passive fishery survey, the increasing of CCF ensures better estimation [8] and three acoustic sensors AST case produce largest number of CCF among the three cases. That is why it gives better results as well as better CV among the three presented cases in this paper.

4. Conclusion

As an accuracy indicator, calculation of statistical error, i.e., CV is a vital task for cross-correlation based population estimation technique of fish and mammals. In this paper, a theoretical and simulated procedure of calculating statistical error of this technique is illustrated. We found from the CV calculation that three acoustic sensors AST case provides more accurate estimation than the other two cases considered in this study. This calculation is important to pursue this technique effectively. Currently, researches are underway to investigate this technique with IoT based systems for effective data transmission.

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