Abundance estimation from different distributions of Damselfish using cross-correlation and three sensors

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Abstract

Damselfish are small, tropical, marine fish of the family Pomacentridae (order Perciformes). They are mostly popular for their aquarium significance. Most damselfish species have bright colors or strongly contrasting patterns which makes them precious for aquarium uses. Beside aquarium values, they are valuable because of their ecological and economic worth. Therefore, an appropriate estimation of their abundance is an important task. In fact, proper abundance estimation is a prerequisite for environmental monitoring and commercial fishery activities. However, conventional techniques of such estimation suffer from several drawbacks. In this paper, we propose an acoustic signal processing technique for estimating the abundance of damselfish that can overcome the major drawbacks of the conventional techniques. In the proposed scheme, the estimation is based on the vocalizing nature of this fish species and cross-correlation technique. Our goal is not only proposing an efficient estimation technique but also measure its performance from different distributions of fishes. We have considered four different distributions - Exponential, Normal, Rayleigh, and Gamma. Among these four distributions, the Exponential distribution of damselfish produce better results in MATLAB simulation for the proposed technique.

Keywords: *Damselfish, bins, chirp signal, cross-correlation, abundance estimation.*

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1. Introduction

Damselfish are familiar for their vocalizing nature [1]. In fact, Damselfish are among the best studied soniferous fish with at least eight of around 29 genera reported to generate sounds [1-3]. Different types of sound production mechanisms are available in fish and mammals. Some of those are swim bladder mechanism, stridulatory mechanism, cavitations mechanism, hydrodynamic mechanism, respiratory mechanism, etc. [4]. The mechanism of sound production in damselfish is hypothesized to involve stridulation of the jaw apparatus or other hard parts [5-6]. Chirp, a sound, commonly produced by males of bicolor damselfish (family: Pomacentridae) possesses an anatomical constraint [7]. In response, females make aggressive sounds. Two types of aggressive sounds, i.e., pops and chirps, are generated by the females. Pops are more commonly generated towards heterospecifics and chirps are usually generated towards conspecifics [8-9].

Damselfish have immense significance in aquarium purposes because of their variable colors and suitable body size. In addition, they are also important for food purposes in the Indian subcontinent and ecological purposes such as cleaning sea water [10]. Consequently, the process of searching and estimating damselfish abundance is paid a colossal importance. Inauspiciously, estimating the actual abundance of fish is tangled. Dynamics of fish population and harsh condition of the ocean are the main obstacles in obtaining accurate data. Many studies have been conducted to estimate the fish abundance. Such estimation techniques can be classified into two types, i.e., non-acoustic and acoustic. Major non-acoustic techniques are removal method of population estimation, minnow traps techniques, visual sampling techniques, environmental DNA technique, prediction-based macro ecological theory, etc. The removal method of population estimation has been applied to estimate small-mammal abundance; certain number of kill traps are set for numerous trapping periods, stated in [11]. The minnow trap is a passive gear for catching small fish species, has long been used in order to estimate fish population [12]. In reference [13], visual census consists of many techniques used to estimate reef fish populations. It has been adopted by the long-term monitoring program (LTMP) to assess reef fish abundance. An attempt to estimate the abundance of aquatic species using environmental DNA concentrations in large stream and river ecosystems is presented in reference [14]. This technique can ensure accuracy but suffers from complexity, high-cost, and dependency on previous data. In reality, most of the non-acoustic techniques are suffered from several problems including some common ones like time consuming nature, poor accuracy, mostly human interaction, costly instruments, etc. Consequently, nowadays, the researchers emphasize on acoustic techniques for fish abundance estimation. The conventional acoustic techniques are echo integration technique, dual-frequency identification sonar

(DIDSON) technique, dual-beam transducer technique, etc. An echo-integrator equation relates fish abundance to echo energy integrated over a time gate corresponding to the depth channel of interest. Parameters include the equivalent beam angle, the expected backscattering cross section per fish, equipment sensitivity, and a time-varied gain correction factor [15]. The DIDSON has been used in environmental management for a decade [16-17]. The limitations of this method are automatic dataset recording and the low range of the detection beam, which decreases accuracy [17]. The aspects of using a narrow wide-beam acoustic transducer for estimating fish abundance are illustrated in reference [18]. In this technique, the acoustic pulse is transmitted with a narrow beam and the echo is received on both the narrow and wide beams [18]. However, the acoustic methods also have some limitations like use of high frequency that harms the inhibitions of fish and mammals, requirement of large number of fishes for proper estimation, and requirement of costly electronic instruments and monitoring. To get rid of these difficulties, in this paper, a straightforward cross-correlation based abundance estimation technique is proposed. In the proposed technique, each damselfish in the estimation area is considered a source of chirp signal and three acoustic sensors are deployed to receive these signals. In the case of three acoustic sensors, two types of topologies are possible. One is acoustic sensors in a straight line and another is acoustic sensors in triangular shape. In this research, we have worked with three acoustic sensors in straight line (ASL) case. The technique is based on cross-correlating the chirp signals which is quite similar to the signal processing approach of node estimation [19-20]. In this article, we have analyzed the results for four different distributions, i.e., Exponential, Normal, Rayleigh, and Gamma, of damselfish to evaluate the performance of the proposed technique.

2. A brief analysis on cross-correlation function

The cross-correlation function (CCF) of time-delayed version of infinite length and unity strength Gaussian signal is to be expressed by a delta function, whose amplitude relays on the attenuation. At the same time, its position will be the delay difference of signals from the center of the CCF.

Then, the CCF for 1st signal source is:

$$(\tau) = \alpha_{11}\alpha_{12}\delta\left(\tau\left[\frac{d_{11}-d_{12}}{S_p}\right]\right) \quad (1)$$

where, d_{11} is the distance between the 1st signal source and 1st receiver, and d_{12} is the distance between the 1st signal source and 2nd receiver.

Assuming the strength of source signal is high enough to overcome attenuations. So, neglecting the attenuations, the CCF for the 1st signal source become:

$$C_1(\tau) = \delta\left(\tau-\left[\frac{d_{11}-d_{12}}{S_p}\right]\right) \quad (2)$$

Likewise, the CCF for Nth signal source is:

$$C_N(\tau) = \delta\left(\tau-\left[\frac{d_{N1}-d_{N2}}{S_p}\right]\right) \quad (3)$$

Then, the CCF for N number of signal sources

$$C(\tau) = \sum_{n=1}^{N}\delta(\tau-\left[\frac{d_{n1}-d_{n2}}{S_p}\right]) \quad (4)$$

It is innate that if N is larger than the number of bins, b and the bins are occupied by more than one delta due to the same delay differences. This increases the amplitude of the deltas of the bins, and thus the CCF is expressed in terms of bins as

$$C_i(\tau) = \sum_{m=1}^{b} p_i\delta_i \quad (5)$$

where, p_i is the amplitude of the delta, δ_i in the ith bin.

The above analysis is verified by simulation in Figure 1, where, 32 sources and 19 bins are considered. Since, signal sources are larger than bins; there is possibility that some bins can be occupied by more than one source and some bins can be empty for time-delay difference. From Figure 1, p_i values are: $p_1 = p_{19} = 4$, $p_4 = p_{10} = p_{13} = 3$, and so on.

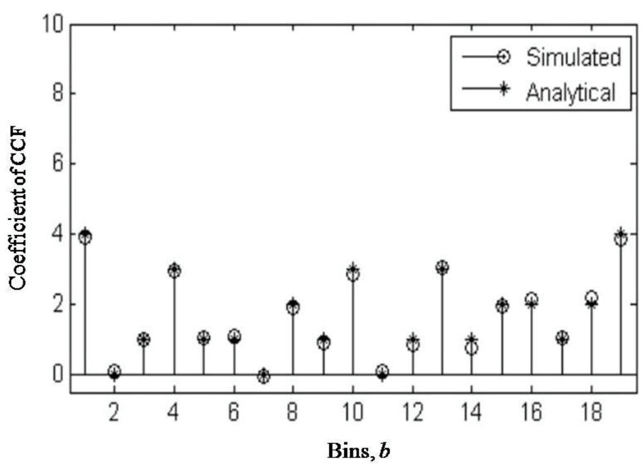


Figure 1: CCF for 32 sources and 19 bins

Using moving average technique of cross-correlation [21-22], we can express the CCF generally by the expression bellow:

$$C(\tau) = \frac{1}{N_s-\tau}\sum_{i=1}^{N_s-\tau} x_i y_{i+\tau} - \left(\frac{1}{N_s}\sum_{i=1}^{N_s} x_i\right)\left(\frac{1}{N_s}\sum_{i=1}^{N_s} y_i\right) \quad (6)$$

where, N_s is the signal length in terms of samples, τ is the time delay of cross correlated signals, x_i and y_i are the ith samples of the two sensor's signals.

We assume Gaussian signal contains zero mean. So, the product of their mean is zero. Hence, the CCF in equation (6) becomes:

$$C(\tau) = \frac{1}{N_s - \tau} \sum_{i=1}^{N_s - \tau} x_i y_{i+\tau} \quad (7)$$

This gives the peaks for the desired bins as follows:

$$\frac{1}{N_s + \tau} \sum_{i=1}^{N_s+\tau} x_i y_{i-\tau}, \quad \dots, \quad \frac{1}{N_s + 1} \sum_{i=1}^{N_s+1} x_i y_{i-1},$$

$$\frac{1}{N_s - 0} \sum_{i=1}^{N_s-0} x_i y_{i+0},$$

$$\frac{1}{N_s - 1} \sum_{i=1}^{N_s-1} x_i y_{i+1}, \quad \dots, \quad \frac{1}{N_s - \tau} \sum_{i=1}^{N_s-\tau} x_i y_{i+\tau}$$

where, the peaks are the strengths of the deltas of equation (5) that can be expressed by following equation [19]:

$$P_1 = \frac{1}{N_s - \tau} \sum_{i=1}^{N_s+\tau} x_i y_{i-\tau}$$

$$P_2 = \frac{1}{N_s + (\tau - 1)} \sum_{i=1}^{N_s+(\tau-1)} x_i y_{i-(\tau-1)}$$

$$\vdots$$

$$p_b = \frac{1}{N_s - \tau} \sum_{i=1}^{N_s-\tau} x_i y_{i+\tau} \quad (8)$$

Theoretical CCF is developed by putting these values in the equation (5) [19].

3. Formulation of CCF

The formulation of CCF of chirp signal is like the formulation of CCF of Gaussian signal [23] which is the starting materials and method to estimate the abundance of damselfish. 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" throughout this paper. Damselfish are considered as the sources of chirp signals, and N damselfish are distributed over the volume of a large sphere, the centre of which lies halfway between the acoustic sensors. A distribution of damselfish by simulation is shown in Figure 2, where, the three reds (+) indicates the acoustic sensors and each damselfish is considered as a source of chirp signal. A constant propagation velocity is considered, called the sound velocity, S_p in the medium. During the formulation of CCF for three acoustic sensors, i.e., H_1, H_2, and H_3, and a damselfish, N_1 the coordinates are considered at (x_1, y_1, z_1), (x_2, y_2, z_2), (x_3, y_3, z_3) and (a, b, c), respectively.

Distance between sensors H_1 and H_2 is

$$d_{DBS_{12}} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \quad (9)$$

Distance between acoustic sensors H_2 and H_3 is

$$d_{DBS_{23}} = \sqrt{(x_2 - x_3)^2 + (y_2 - y_3)^2 + (z_2 - z_3)^2} \quad (10)$$

We have considered, $d_{DBS12} = d_{DBS23} = d_{DBS}$, which implies that two CCFs are possible.

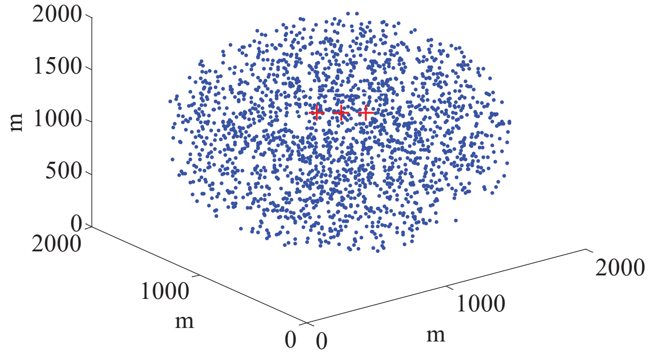


Figure 2: A distribution of damselfish in 3D space with three acoustic sensors.

Figure 3 shows a 3D space of a single damselfish N_1 and three acoustic sensors H_1, H_2 and H_3

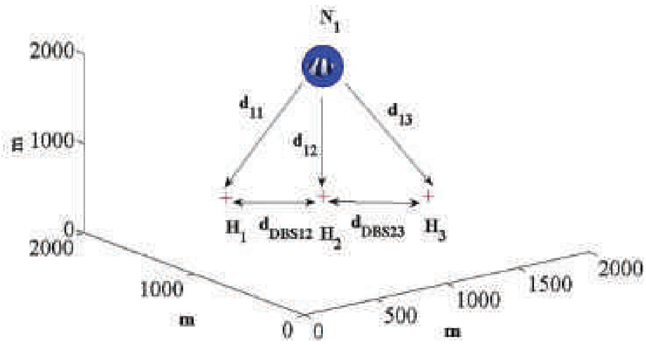


Figure 3: From a distribution of damselfish in 3D space, we consider one fish with three acoustic sensors

Here, we consider that the chirp signal coming from N_1 is S1(t), which is finitely long. The signal received by acoustic sensors H_1, H_2 and H_3 are S_{r11}, S_{r12}, and S_{r13}, respectively:

$$S_{r11}(t) = \alpha_{11} S_{11}(t - \tau_{11}) \quad (11)$$

$$S_{r12}(t) = \alpha_{12} S_{12}(t - \tau_{12}) \quad (12)$$

$$S_{r13}(t) = \alpha_{13} S_{13}(t - \tau_{13}) \quad (13)$$

where, α_{11}, α_{12}, and α_{13} are the attenuation due to absorption and dispersion in the medium, and τ_{11}, τ_{12}, and τ_{13} are the respective time delays for the chirp signals to reach the acoustic sensors.

The CCFs for three acoustic sensors in ASL case are:

$$C_1(\tau) = \int_{-\infty}^{+\infty} S_{11}(t) S_{12}(t - \tau_{11}) d\tau \quad (14)$$

$$C_2(\tau) = \int_{-\infty}^{+\infty} S_{12}(t) S_{13}(t - \tau_{12}) d\tau \quad (15)$$

To find out the CCFs for N damselfish, we have to take the total chirp signals received by the three acoustic sensors.

Now the composite signals received by H_1, H_2 and H_3 are:

$$S_{rt1} = \sum_{j=1}^{N} \alpha_{j1} S_j(t - \tau_{j1}) \quad (16)$$

$$S_{rt2} = \sum_{j=1}^{N} \alpha_{j2} S_j(t - \tau_{j2}) \quad (17)$$

$$S_{rt3} = \sum_{j=1}^{N} \alpha_{j3} S_j(t - \tau_{j3}) \quad (18)$$

Therefore, the total CCFs are:

$$C_{12}(\tau) = \int_{-\infty}^{+\infty} S_{rt1}(t) S_{rt2}(t - \tau)\, d\tau \quad (19)$$

$$C_{23}(\tau) = \int_{-\infty}^{+\infty} S_{rt2}(t) S_{rt3}(t - \tau)\, d\tau \quad (20)$$

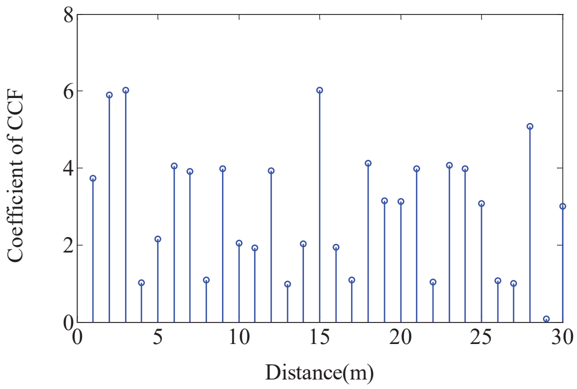


Figure 4: Bins in the cross-correlation process of the proposed technique

These take the form of series of delta functions, as it is a cross-correlation of two signals which is the summation of several chirp signals where one signal is fundamentally a delayed copy of the other. Figure 4 shows the bins of cross-correlation process of the proposed technique.

4. Estimation process of damselfish

We have known that chirp pulses are generated by a school of damselfish during swimming within their territory. A relationship between sound characteristics and swimming behaviour during the signal jump is described in [7]. However, for simplicity, in the simulation, a negligible amount of power difference among the chirp pulses transmitted by each damselfish was considered.

4.1 Different distributions of damselfish

Different distributions of fishes are practical phenomenon. In our research, we have considered four distributions, i.e., Exponential, Normal, Raleigh, and Gamma of damselfish. For exponential distribution the Probability density function (PDF) is $y = f(x|\mu) = 1/\mu \times e^{-x/\mu}$, where μ is the mean parameter, for Rayleigh distribution the PDF is $y = f(x|\mu) = x/\beta^2 \times e^{-x^2/2\beta^2}$, where, β is the scale parameter, and for Normal distribution the PDF is $y = f(x|\mu, s) = 1/\alpha \times \sqrt{2} e^{-(x-\mu)^2/2s^2}$, where, s is the standard deviation. In Gamma Distribution, three types of parameter are commonly used. They are a shape

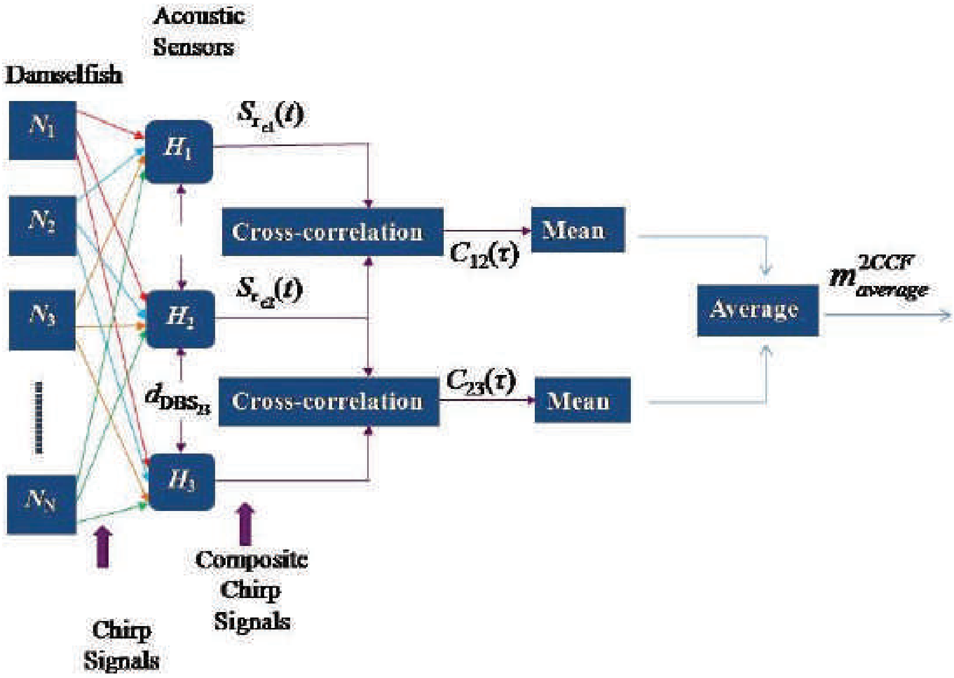


Figure 5: Block diagram representation of cross-correlation formulation process

parameter k_1, scale parameter β, and a mean parameter $\mu = k_1/\beta^*$, where, β^* is an inverse scale parameter and $\beta^* = 1/\vartheta$. However, every parameter is positive and real number.

4.2 Chirp Signal

Generally, croaker kinds of fish produce a sound, which is akin to a chirp signal. From a sound analysis of *Plectroglyphidodon lacrymatus* and *Dascyllus aruanus* species of damselfishes, it was found that their generated chirps consisted of pulse trains of 12–42 short pulses of three to six cycles, with durations varying from 0.6 to 1.27 ms; peak frequency varied from 3400 Hz to 4100 Hz [24]. However, a chirp signal is a swept-frequency signal, which has a time varying frequency. Such a signal can be expressed as [25]:

$$X(t) = A\cos\left[\left\{2\pi\left(\frac{(f_2 - f_1)t^2}{2d} + f_1 t\right)\right\} + P\right] \quad (21)$$

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.

4.3 Abundance estimation from theory

It is acknowledged that the CCF follows the binomial probability distribution [19]. Consequently, here N damselfish and b bins were used. Then the expected value, i.e., the mean, m of the CCF is defined as [20, 26].

$$m = \frac{N}{b} \quad (22)$$

In the cross-correlation process, b can be achieved from the following equation [19, 27].

$$b = \frac{2 \times d_{DBS} \times S_R}{S_P} - 1 \quad (23)$$

where, S_R is the sampling rate, d_{DBS} is the distance between equidistant acoustic sensors, and S_p is the speed of sound propagation.

So, we can rewrite the equation (22) as follows.

$$N = b \times m \quad (24)$$

This is the relationship between the abundance of damselfish N and the mean m of the CCF. Since b is known and m be measured from the CCF, we can estimate the number of damselfish N. For three acoustic sensors in ASL case, the estimation parameter $m^{2CCF}_{average}$ is attained by following equation:

$$m^{2CCF}_{average} = \frac{m_{12} + m_{23}}{2} = \frac{\frac{N}{b_{12}} + \frac{N}{b_{23}}}{2} \quad (25)$$

where, m_{12} is the mean of CCF from the acoustic sensors H_1 and H_2 and m_{23} is the mean of CCF from the acoustic sensors H_2 and H_3.

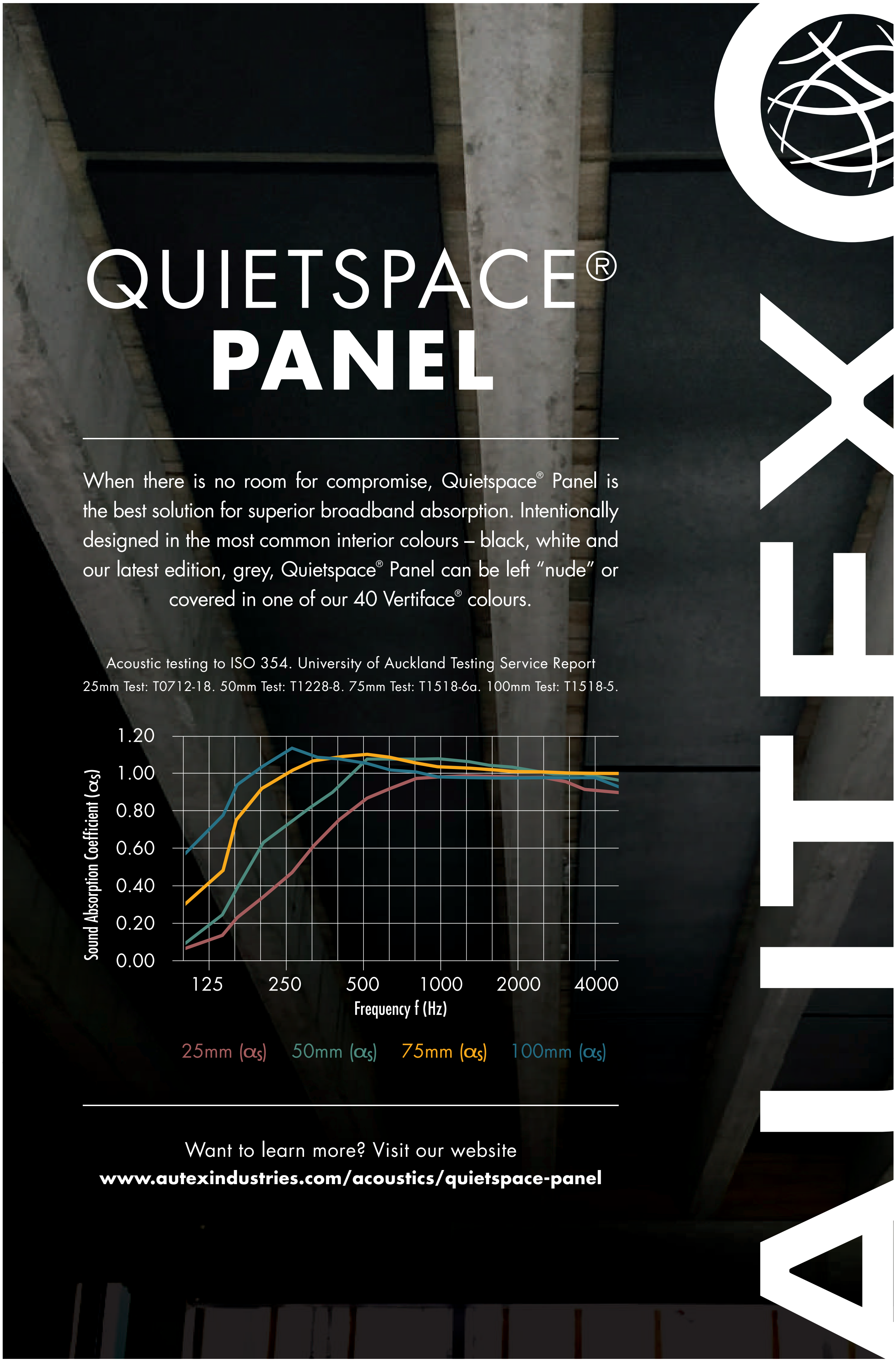
If b_{12}= b_{12}= b, then equation (25) can be simplified as follows:

$$m^{2CCF}_{average} = \frac{m_{12} + m_{23}}{2} = \frac{N}{b} \quad (26)$$

The block diagram in Figure 5 shows the process of cross-correlation formulation for damselfish estimation with three acoustic sensors in a line.

4.4 Abundance estimation from simulation

In this section, simulations were executed considering that three acoustic sensors were deployed in a line on the centre of a 3D sphere. The plots are found for four different distributions, i.e., Exponential, Normal, Rayleigh, and Gamma. All the simulations were accomplished by MATLAB programs. The parameters in the table 1 are common for all the four types of distributions. The simulation results were obtained by averaging 500 iterations.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1.00
0.80
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2000
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Frequency f (Hz)
25mm (αs)
50mm (αs)
75mm (αs)
100mm (αs)
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Table 1: Parameters in Simulation

Parameters	Values
Dimension of the sphere	2000m
Distance between the equidistant acoustic sensors, d_{DBS}	0.5m
Speed of propagation, S_p	1500 m/s
Sampling rate, S_R	60 KSa/s
Absorption coefficient, a	1
Dispersion factor, k	0
Number of bins, b	39
Mean parameter μ for all the three distributions	5
Standard deviation s for normal distribution	2
Scale parameter β for Rayleigh distribution	2
Scale parameter β for Gamma distribution	1
Shape parameter k_1 for Gamma distribution	5

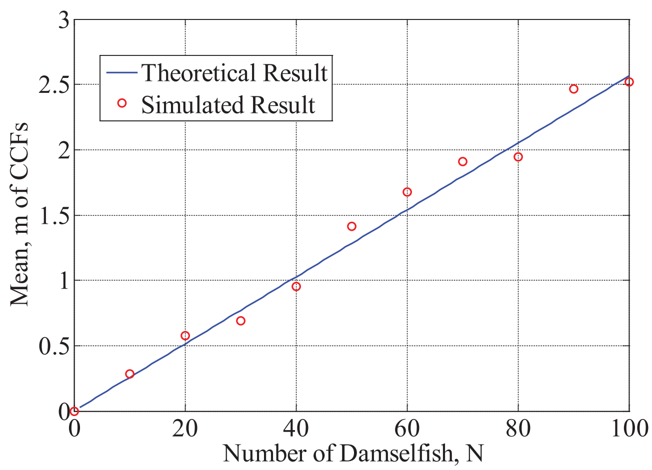

Figure 6(a) - Exponential distribution

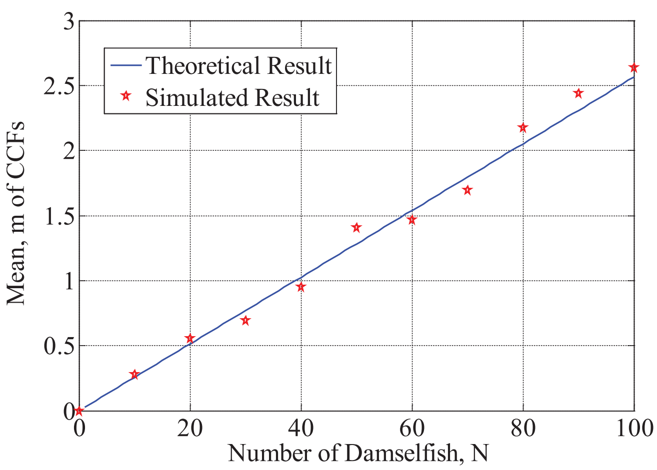

Figure 6(b) - Normal distribution

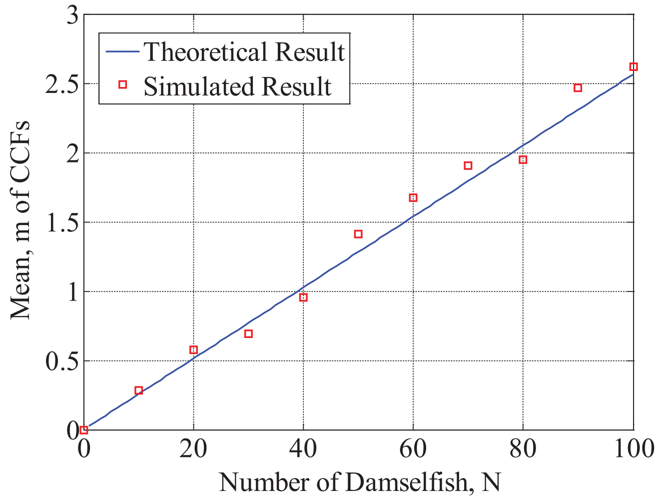

Figure 6(c) - Rayleigh distribution

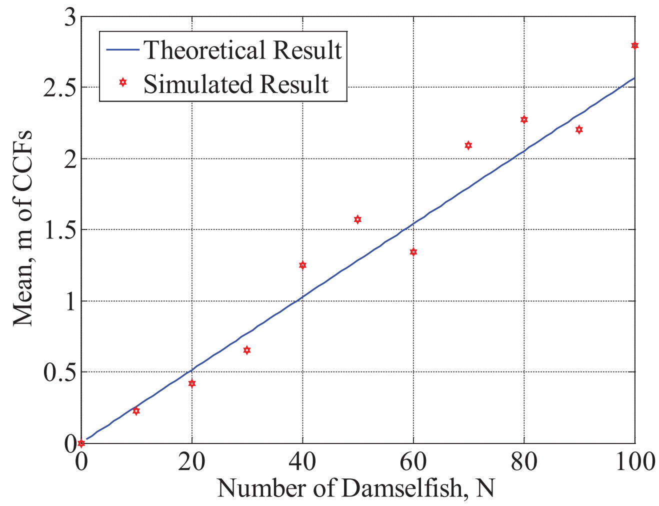

Figure 6(d) - Gamma distribution

Figure 6: Number of damselfish, N vs. mean, m of the CCFs

In Figures 6 and 7, straight lines (blue) correspond the theoretical results and reds (circles, pentagons, squares, & hexagons), in the Figures (a)-(d), respectively, correspond to simulated results for four different distributions.

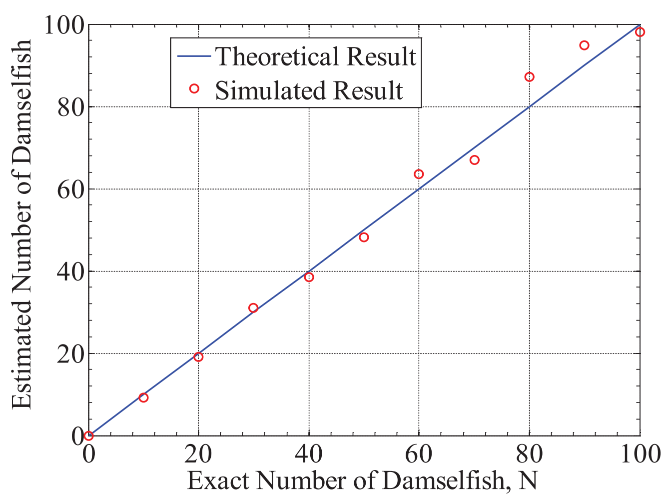

Figure 7(a) - Exponential distribution

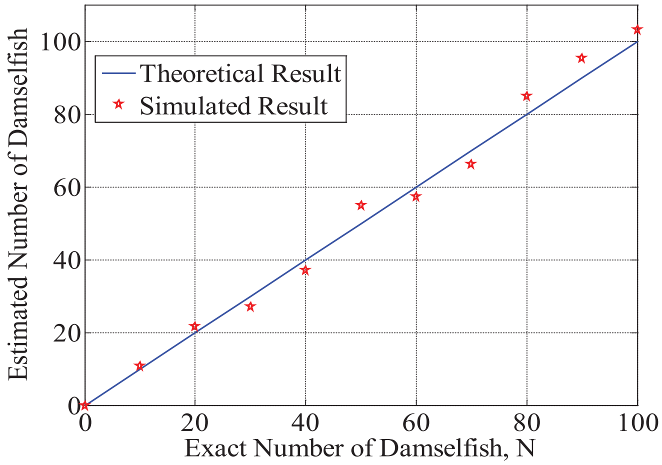

Figure 7(b) - Normal distribution

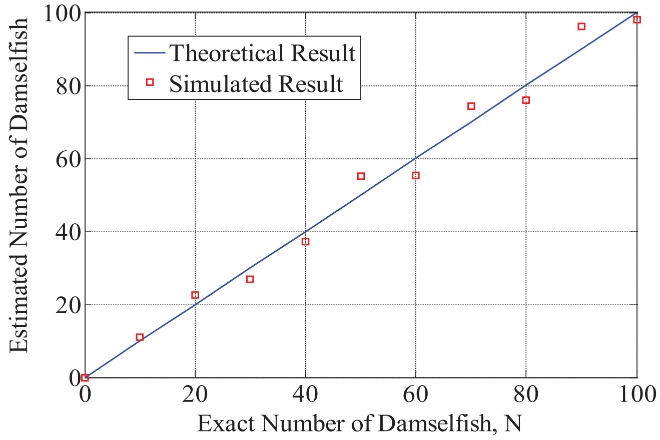

Figure 7(c) - Rayleigh distribution

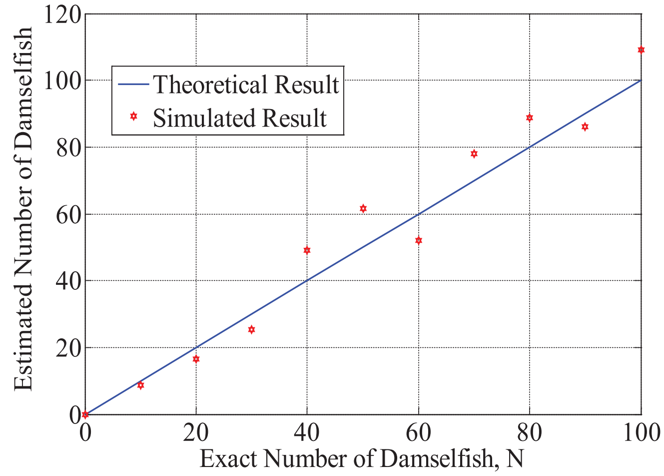

Figure 7(d) - Gamma distribution

Figure 7: Actual number of damselfish versus estimated number of damselfish

Figure 6 shows the mean, *m* of CCFs with respect to the number of damselfish, *N* for different distributions. On the other hand, Figure 7 shows a variation between the estimated number of damselfish from actual quantity. From the two Figures 6 and 7, it is seen that the theoretical and simulated results are very close to each other, which signifies the strength of the proposed abundance estimation technique.

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4.5 Discussion

From the analysis of simulation results in Figures 6 and 7, we can come to a decision that the Exponential distribution of damselfish provides better results for the proposed abundance estimation technique.

Table 2: Experimental and Theoretical Data of CCF and Percentage of Error for Exponential Distribution

Actual number of damselfish, N_a	Mean of CCF from simulation	Estimated number of damselfish, N_e	Percentage of error, $(N_a - N_e)/N_a$ *100%
0	0	0	0
10	0.238	9.27	7.3%
20	0.490	19.13	4.35%
30	0.796	31.05	3.5%
40	0.987	38.48	3.8%
50	1.235	48.16	3.68%
60	1.631	63.61	6.02%
70	1.714	66.87	4.47%
80	2.133	83.18	3.98%
90	2.431	94.71	5.23%
100	2.514	98.06	1.96%

From Table 2, we find the simulated results for Exponential distribution of damselfish. For the case of 30 and 100 damselfish, the simulation results provide 31 and 98 damselfish, consecutively. The percentage of errors is 3.5% and 1.96%, consecutively. This shows a good indication of accuracy of our proposed estimation technique.

However, this method has some limitations like negligence of multipath interference, assuming the delays to be integers and analogous, and assuming a negligible amount of power differences among the chirp pulses transmitted by each damselfish.

5.0 Conclusion

As a precious fish species, abundance estimation of damselfish carries a great significance. In the past, such estimations were precluded by several impediments. Our goal was to investigate a suitable technique that can overcome the major limitations of conventional techniques. Performance analysis of the proposed technique using different fish distributions was also our similar aim. Therefore, we have proposed straightforward and statistic-based techniques that can erudite major obstacles of the conventional techniques of abundance estimation. From the analysis of the simulation results using four different distributions of damselfish, we found that the Exponential distribution of damselfish provide better performance.

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Acoustics Quiz

Q1 What is 'bioacoustics' the study of?

Q2 Yes or No? The white noise spectrum is flat?

Q3 What does the following formula solve? $1449.2 + 4.6*T – 0.55*T_2 + 0.00029*T_3 + (1.34-0.01*T)*(s-35) + 0.016*z$ (m/s)?

Q4 What is the approximate. speed of sound in salt water?

Q5 Who was the founder of the deciBel scale (dB)?

Q6 What is the Fresnel Number?

Q7 True or False? Snell's law is also known as law of reflection.

Q8 Briefly describe what is meant by the 'free field region'.

Q9 True or False? - Loudness is a subjective perception.

Q10 Briefly describe the concept of pitch.

Q11 What is the hearing range humans are most sensitive to?

Q12 What is meant by the term 'Binaural' ?

Q13 What is the Franssen Effect?

Q14 What is the Lombard Effect?

Q15 What is a direct drive hearing system?

Q16 What does Misophonia mean?

Q17 Why don't we like the sound of our own voice?

Q18 True or False? - Permanent hearing loss can occur suddenly if a person is exposed to very loud impact/explosive sounds.

Q19 In the field of occupation noise what is mean by the concept of 'over protection'?

Q20 What is the Speech Interference Level (SIL)?