Underwater Acoustic Noise Characteristics Of Shallow Water In Tropical Seas

Ahmad Zuri Sha'ameri[1] ,Yasin Yousif Al-Aboosi[1,2] , Nor Hisham Haji Khamis[1]
[1]Faculty of Electrical Enginnering, Universiti Teknologi Malaysia, 81310, Skudai, Johor, Malaysia.
[2] College of Engineering, University of Mustansiriyah, Baghdad, Iraq.
zuri@fke.utm.my, ymyasin2@live.utm.my, hisham@fke.utm.my

***Abstract*— In the underwater communication and target locating, the biggest challenge is to reduce the effect of underwater acoustic noise (UWAN). An experimental model is presented in this paper to characterize noise in the acoustic underwater channel in shallow water. Data is measured from different depths located in the Tanjung Balau, Johor, Malaysia. Most applications assume the UWAN as additive and Gaussian. However, the UWAN is not just thermal noise but a combination of turbulence, shipping and wind noises. Site-specific noise in shallow water often contains significant non-Gaussian components. Thus, it is appropriate to assume UWAN as colored rather than white with non-Gaussian probability density function (pdf). The real-time noise data are analyzed for different depths to determine the statistical properties such as power spectral density (PSD), autocorrelation function and pdf. The results show the UWAN has a non-Gaussian pdf, and is colored with a power spectral density that decays at a rate of approximately 20 dB/decade. Also, the power decreases with increasing depth as the distance from the surface at approximately 10 dB.**

Keywords- Underwater communications; Underwater acoustic noise; color noise; non-Gaussian statistics; non-white statistics; noise distribution.

I. INTRODUCTION

Efficient communication and target locating are essential for maritime applications such as oceanographic studies, offshore oil exploration and defense application [1]. The main motivation to use sound waves over the electromagnetic signals is due to the relatively lower attenuation in the underwater environment. However, the main challenge is to find the usable frequency band for sound (around 10kHz) and mitigate the various disturbances due to both natural (seismic, wind, etc.) and manmade (shipping, other machinery noises) [2].

The underwater acoustic noise (UWAN) consists of ambient noise and site-specific noise [3]. Ambient noise is always present in the background of the deep sea. Site-specific noise for example exists for ice cracking in polar region and acoustic noise due snapping shrimp in warmer waters. Other sources are from turbulence, breaking waves, rain, and distant shipping. While the UWAN is often approximated as white noise, in practice it is colored exhibiting a decaying power spectral density (PSD) with a rate of decay of approximately 18 dB/decade [3].. As the attenuation of sound is a frequency-dependent process, the ocean acts as a low-pass filter for ambient noise. Thus, the UWAN PSD is usually ($1/f^{\,n}$) where noise has more power at lower frequencies and less power at higher frequencies [4].

The significant non-Gaussian components in UWAN [3] results in a pdf with extended tails. This shape characterizes the impulsive behavior due to the high incidence of large amplitude noise events [5-7]. Thus, the main goal of this paper is to determine the statistical properties of underwater acoustic noise based on the power spectral density (PSD), autocorrelation function and pdf. The paper is organized as follows: in Section II, a brief introduction of characteristics of ambient noise, the statistical properties are described in Section III, results explain in section IV and conclusions are summarized in section V.

II. UNDERWATER ACOUSTIC NOISE

Characteristics of UWAN in the ocean have been well defined [5] with the major components are turbulence, shipping, wind and thermal noise. Each component has a dominating influence at the different portions of the frequency spectrum. The contributions of the major noise sources can be expressed through empirical formulae, which provide PSD of each source relative to frequency f [kHz] in [dB re µ Pa per Hz] [6, 7]. The power spectrum due to turbulence, shipping, wind and thermal noise are expressed as:

$$N_t(f) = 17 - 30logf \tag{1}$$

$$N_s(f)40 + 20(s-5) + 26logf - 60\log(f+0.03) \tag{2}$$

$$N_w(f) = 50 + 7.5w^{1/2} + 20logf - 40\log(f+0.4) \tag{3}$$

$$N_{th}(f) = -15 + 20logf \tag{4}$$

where f is the frequency in kHz. The total noise PSD for a given frequency f [kHz] is then:

$$S_{xx}(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f) \tag{5}$$

Fig.1 shows the empirical noise PSD for different conditions of shipping activities and with wind speeds of 3.6 m/sec (7 knots). It is observed that each noise source is dominant in specific frequency bands. Turbulence noise is dominant in the frequency band (0.1Hz - 10Hz), while shipping activities is the major factor contributing to noise in the frequency region (10Hz - 200Hz). Shipping activities are usually weighted by a factor *s* which ranged from between 0 and 1 representing low and high activity respectively. The frequency region (0.2 kHz - 100 kHz) is dominated by surface motion, which is mainly affected by wind (*w* is the wind speed in m/s). For frequencies higher than (100 kHz) thermal noise is dominant. Besides, these noise sources depend on weather and other environment

978-1-4799-7635-5/14 $31.00 © 2014 IEEE
DOI 10.1109/ICCCE.2014.34

factors. Thus, the UWAN PSD shown in Fig. 1 is located in the area between the two curves ($1/f^2$) and ($1/f^3$).

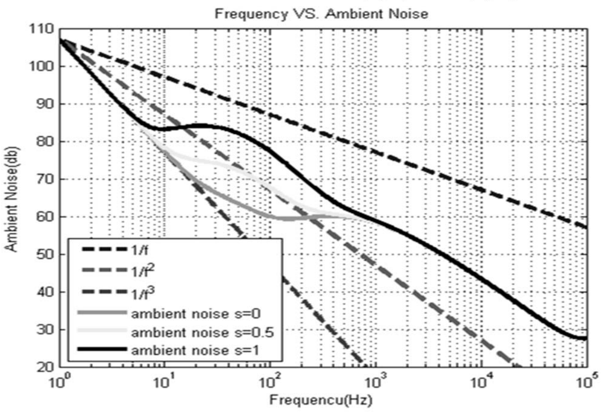


Figure 1. The noise PSD level in dB re µ Pa per Hz based on empirical formulae with wind speed 3.6 m/s (7 knots) and different Shipping noise is presented for high (s = 1), moderator (s = 0.5), light (s= 0) shipping activities.

The UWAN in shallow water is more difficult to model or predict compared to the deep water case, due to greater variability in both time and location. Typical shallow-water environments are found for water depths down to 200m, while deep-water environments are found in all oceans at depths exceeding 2000m [4]. In [5, 6], three major noise sources in shallow water environments are identified as wind noise, biological noise (due to snapping shrimp whose noise signature has a high amplitude and wide bandwidth) and shipping noise. The UWAN power also decreases with increasing depth as the distance from the surface and the shipping and wind noise becomes more distant. In general, the UWAN has been shown to be 9dB higher in shallow water than deep water [7].

III. STATISTICAL PROPERTIES AND ESTIMATION

Random signals unlike deterministic signals are best characterized by their statistical properties. For this paper, the statistical properties used for UWAN are autocorrelation function, PSD and PDF.

A. Auto-Correlation Function

A random signal can be characterized in terms of how its value at one time, t, depends on the value at some other time, $(t+\tau)$. This is termed as the auto-correlation function which is the cross-correlation of a signal with itself [8]. The autocorrelation function is given by:

$$r_{xx}(\tau,t) = E[x(t)x(t+\tau)] \qquad (6)$$

where $E[\ ]$ is the expectation operator. If the random process is wide sense stationary, the autocorrelation function can be expressed as:

$$r_{xx}(\tau,t) = r_{xx}(\tau) = E[x(t)x(t+\tau)] \qquad (7)$$

The function depends only on relative time rather than the absolute t. In the normalized case, $0 \le r_{xx}(\tau) \le 1$ where a zero indicates no dependency and a one a strong dependency [9].

B. Power Spectrum Density(PSD) and Estimation

The PSD represents the frequency representation of a random process. Estimate the PSD is performed by power spectrum estimation (PSE). Generally, there are two types of (PSE) method: parametric and nonparametric. Unlike parametric PSE, nonparametric PSE does not make any assumption on the data generating process. The relationship between the autocorrelation function and the PSD is defined by the Wiener-Khinchine theorem [10].

$$S_{xx}(f) = \int_{-\infty}^{\infty} r_{xx}(t)e^{-j2\pi ft}\,dt \qquad (8)$$

$$r_{xx}(\tau) = \int_{-\infty}^{\infty} S_{xx}(f)e^{j2\pi f\tau}\,df \qquad (9)$$

Power spectrum in Eq. (8) evaluated at f=0 yields

$$S_{xx}(0) = \int_{-\infty}^{\infty} r_{xx}(\tau)\,d\tau \qquad (10)$$

Similarly, letting τ=0 in the autocorrelation function in Eq. (9) results in

$$r_{xx}(0) = \int_{-\infty}^{\infty} S_{xx}(f)\,df \qquad (11)$$

Eq. (10) implies that an autocorrelation function is integrable if $S_{xx}(0) < \infty$. On the other side, the PSD $S_{xx}(f)$ is integrable when $r_{xx}(0) < \infty$ as indicated in Eq. (11). Both are the usual cases for conventional colored noise. However, this is different for colored noise of ($1/f^n$) type which has the property $S_{xx}(0)= \infty$ [9].

There are five common non-parametric power spectrum estimation (PSE) [10]: periodogram, modified periodogram, Welch's method,Bartlett's method, and Blackman-Tukey method. Periodogram as a PSE is limited since it is a nonconsistent where the estimate variance for white noise does not reduce with signal length. Other methods attempt to minimize this problem and the Welch's method is among the method that provides consistent PSE.

The Welch's method divides the time series data into (possibly overlapping) segments, compute a modified periodogram of each segment, and then averaging the PSE. The averaging effect introduced in this method decreases the variance in the PSE. Further reduction in variance is achieved by overlapping the segments.

If the signal is sampled at a normalized sampling frequency, the Welch method [10] can be expressed as:

$$P_{welch}(e^{jw}) = \frac{1}{KLU}\sum_{i=0}^{K-1}\left|w(n)x(n+iD)e^{-jnw}\right|^2 \qquad (12)$$

where K is the number of segments, and L is the length of each segment. The normalization factor is:

$$U = \frac{1}{L}\sum_{n=0}^{L-1}|w(n)|^2 \qquad (13)$$

where D is the offset between two consecutive segments.

C. Probabilty Density Function:

The standard model of noise is Gaussian, additive, independent at each pixel and independent of the signal intensity. In applications, Gaussian noise is most usually used as additive white noise to yield additive white Gaussian noise (AWGN) [8]. It has shaped probability distribution function given by:

$$P_Z(z) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(z-\mu)^2}{2\sigma^2}} \tag{14}$$

where μ represents the mean value and σ the standard deviation.

Several publications [3][11] have reported that the (UWAN) does not follow the normal distribution. Instead, the pdf has extended tails shape reflecting an impulsive behaviour due to the high incidence of large amplitude noise event [3]. The noise follows the alpha-stable distribution class where the characteristic equation has an inverse. Without knowledge of pdf in a closed form, the only solution is to use numerical methods. An alternative modelling method is by means of empirical analysis of the noise samples obtained directly from the underwater environment [11].

The Student's t distribution is associated with the Gaussian distribution and is characterized by wider tails. It is used in the estimation of the population mean for a small number of samples and unknown population standard deviation. The pdf is expressed by:

$$p_x(x) = \frac{\Gamma\left(\frac{\boldsymbol{v+1}}{\boldsymbol{2}}\right)}{\boldsymbol{\sigma\sqrt{v\pi}}\,\Gamma\left(\frac{\boldsymbol{v}}{\boldsymbol{2}}\right)}\left[\frac{\boldsymbol{v}+\left(\frac{\boldsymbol{x-\mu}}{\boldsymbol{\sigma}}\right)^2}{\boldsymbol{v}}\right]^{-\left(\frac{\boldsymbol{v+1}}{\boldsymbol{2}}\right)} \tag{15}$$

where $\Gamma(\cdot)$ is the gamma function with location parameter μ, scale parameter $\sigma > 0$, and shape parameter $v > 0$. As v increases, the Student's t distribution approaches a Gaussian distribution.

IV. RESULTS

The noise samples during experiments conducted in shallow water at Tanjung Balau, Johor,-Malaysia (Latitude 1° 35.169'N) and (Longitude 104° 16.027'E) on the 5 November 2013. The signals were received through a broadband hydrophone (7 Hz ~ 22 kHz) model DolphinEAR 100 Series, located about 5000 meters from the shore and at different depths from 1 to 9 meters with sea floor at a depth of 10 meters. Wind speed was about 7 Knots and and temperature at the surface of sea about 27 C° .

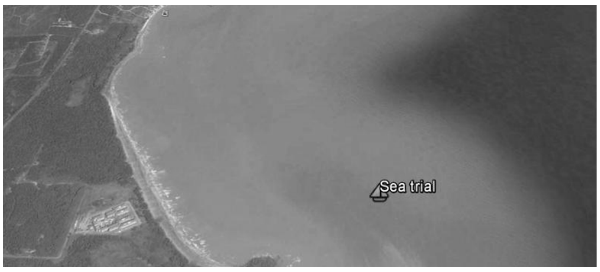
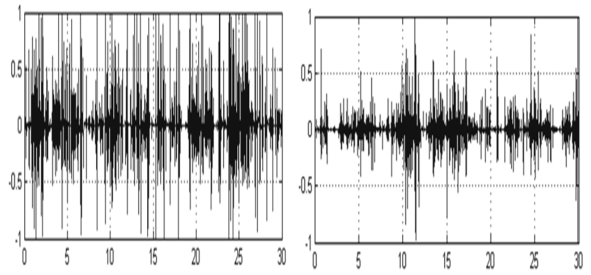


Figure 2 . Test site for experiment.

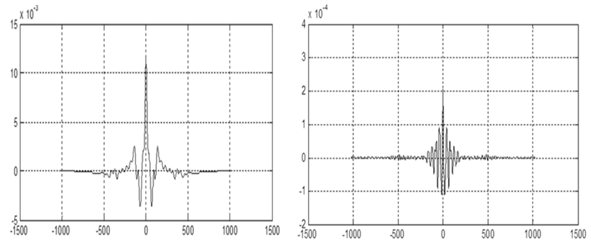
The underwater acoustic noise (UWAN) is recorded by the hydrophone which converts the signal to the discrete time representation for further processing and storage in a personal computer. Power spectrum is estimated using Welch's modified periodogram technique and the data were analyzed for various depths. The setup for the PSE are: sampling frequency 8000Hz, window type Hanning , N-point FFT(fast Fourier transform) 2048, FFT window size 256 and overlapping 50%.

Fig. 3 shows the time representation waveform of the collected data with the two different depths of 5 meters and 9 meters. Unlike white Gaussian noise, the biased autocorrelation function is not similar to the unit impulse which means that the noise samples are correlated and considered colored. The value of the autocorrelation function at τ=0 represented the noise power Shows clearly when the depth increase the noise power reduces also.

Fig.4 shows the PSE analyzed at different depths. Clearly, underwater acoustic noise has a decaying power spectral density and when the depth increases the noise power is reduced by about 10 dB from surface to bottom. In general, the power spectrum estimates are located between ($1/f^2$) and ($1/f^3$). This confirms that the noise is not white but colored.



(a) Time representation 5 meters depth. (b) Time representation 9 meters depth.



(c) Autocorrelation 5 meters depth. (d) Autocorrelation 9 meters depth.

Figure 3. Time representation waveform and autocorrelation function of the underwater acoustic noise for two different depths 5 meters and 9 meters .

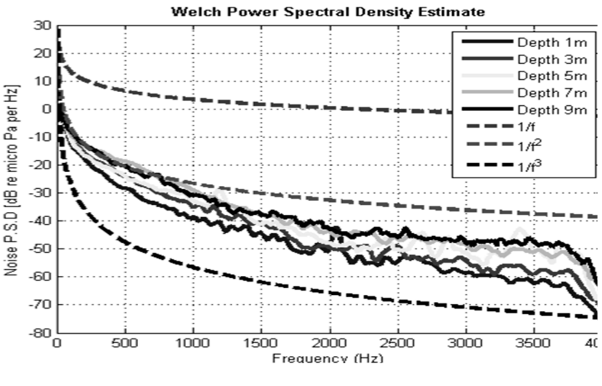


Figure 4. Welch Noise PSD estimate for different depths.

Fig. 5 shows that the power spectral density (log scale) of the UWAN obtained from real field decays at a rate of approximately 20 dB/decade. The result obtained differs from the result mentioned in reference [3] by 2 dB, where the power spectral density decays at a rate of approximately 18 dB/decade.

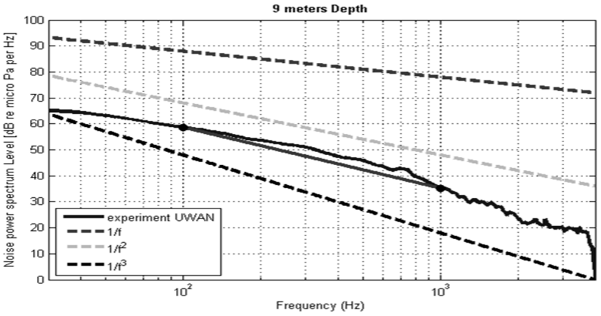
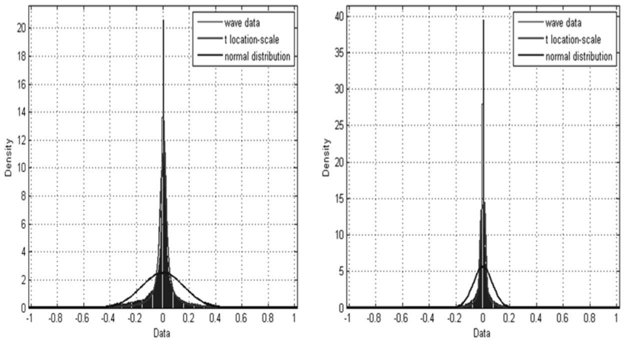


Figure 6. Welch Noise PSD estimate at 9 meters depths in logarithm scale.

Fig. 6 shows the probability density function of underwater acoustic noise obtained from the time representation for two different depths of 5 meters and 9 meters and the best t location-scale fit for the probability density function of noise using The Distribution Fitting Tool in the MATLAB.



(a) 5 meters Depth (b) 9 meters Depth

Figure 6. Best t location-scale fit for the probability density of real UWAN.

V. CONCLUSION

The characteristics of UWAN in tropical seas have an accentuated impulsive behaviour. The power spectral density of the noise is not a constant across the frequency range, and the correlation function of the noise is not a delta function. Thus, the noise with these characteristics is considered as colored noise. Field trials have shown that the noise power decrease from surface of sea to the 9 meters depth at approximately 10 dB and the power spectral density of the ambient noise decays at a rate of approximately 20 dB/decade. The noise amplitude distribution fitted with the (t Location-Scale Distribution) which is associated with the standard Gaussian distribution shows wider tails. Therefore, the UWAN does not follow the assumption of white noise nor a Gaussian distribution.

ACKNOWLEDGMENT

The authors would like to thank Universiti Teknologi Malaysia (UTM) under project Vot No. Q.J130000.3023.00M13 and Ministry of Higher Education (MOHE) Malaysia and the University of Mustansiriyah, Iraq for supporting this research.

REFERENCES

[1] P. H. Dahl, J. H. Miller, D. H. Cato, and R. K. Andrew, "Underwater ambient noise," Acoustics Today, vol. 3, pp. 23-33, 2007.

[2] S. S. Murugan, V. Natarajan, and R. R. Kumar, "Estimation Of Noise Model And Denoising Of Wind Driven Ambient Noise In Shallow Water Using The Lms Algorithm," Acoustics Australia, vol. 40, p. 111, 2012.

[3] M. Stojanovic and J. Preisig, "Underwater acoustic communication channels: Propagation models and statistical characterization," Communications Magazine, IEEE, vol. 47, pp. 84-89, 2009.

[4] M. Chitre, J. Potter, and O. S. Heng, "Underwater acoustic channel characterisation for medium-range shallow water communications,"in OCEANS'04. MTTS/IEEE TECHNO-OCEAN'04, 2004, pp. 40- 45.

[5] R. J. Urick, "Principles of underwater sound. 1983," ed: McGraw-Hill, 1983.

[6] T. Melodia, H. Kulhandjian, L. C. Kuo, and E. Demirors, "Advances in Underwater Acoustic Networking," Mobile Ad Hoc Networking: Cutting Edge Directions, Second Edition, pp. 804-852, 2013.

[7] G. Burrowes and J. Y. Khan, "Short-Range Underwater Acoustic Communication Networks," Autonomous Underwater Vehicles, Mr. Nuno Cruz (Ed.), 2011.

[8] A. Yaglom, Correlation Theory of Stationary and Related Random Functions: Vol.: 1: Basic Results: Springer-Verlag, 1987.

[9] M. L. a. W. Zhao, "Review Article On 1/f Noise," Hindawi Publishing Corporation Mathematical Problems in Engineering,Volume 2012, Article ID 673648, 2012.

[10] H. R. Gupta and R. Mehra, "Power Spectrum Estimation using Welch Method for various Window Techniques." International Journal of Scientifc Research Enginering & Technology (IJSRET),Vol. 2 (6) ,pp. 389-392 , 2013.

[11] Panaro, F. Lopes, L. M. Barreira, and F. E. Souza, "Underwater Acoustic Noise Model for Shallow Water Communications," in Brazilian Telecommunication Symposium, 2012.