TELKOMNIKA, Vol.15, No.1, March 2017, pp. 314~321
ISSN: 1693-6930, accredited **A** by DIKTI, Decree No: 58/DIKTI/Kep/2013
DOI: 10.12928/TELKOMNIKA.v15i1.4510

Diurnal Variability of Underwater Acoustic Noise Characteristics in Shallow Water

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Abstract

The biggest challenge in the underwater communication and target locating is to reduce the effect of underwater acoustic noise (UWAN). An experimental model is presented in this paper for the diurnal variability of UWAN of the acoustic underwater channel in tropical shallow water. Different segments of data are measured diurnally at various depths located in the Tanjung Balau, Johor, Malaysia. Most applications assume that the noise is white and Gaussian. However, the UWAN is not just thermal noise but a combination of turbulence, shipping and wind noises. Thus, it is appropriate to assume UWAN as colored rather than white noise. Site-specific noise, especially in shallow water often contains significant non-Gaussian components. The real-time noise segments are analyzed to determine the statistical properties such as power spectral density (PSD), autocorrelation function and probability density function (pdf). The results show the UWAN has a non-Gaussian pdf and is colored. Moreover, the difference in UWAN characteristics between day and night is studied and the noise power at night is found to be more than at the day time by around (3-8dB).

Keywords*: underwater acoustic noise, colored noise, non-gaussian statistics*

1. Introduction

The ability to communicate effectively underwater has many applications for marine researchers, sonar applications, oceanographers, marine commercial operators, off-shore oil industry and defense organizations [1, 2]. As electromagnetic waves propagate poorly in sea water, acoustics are the most suitable waves for underwater communications. However, they are largely affected by various types of noise in the shallow and deep waters which are due to multiple sources (e.g. shipping, wind) and no one source dominate [3, 4]. The underwater environment consists of ambient noise and site-specific noise [2]. Ambient noise is always present in the background of the deep sea. Site-specific noise, for example, exists as a result of ice cracking in the polar region and the snapping shrimps in warm waters. On the other hand, ambient noise is often approximated as Gaussian and in practice is colored exhibiting a decaying power spectral density (PSD) at a rate of approximately 18 dB/decade [2]. The noise observed on the site has significant non-Gaussian components [2]. As the attenuation of sound in the ocean is a frequency-dependent process, the ocean acts as a low-pass filter for ambient noise. The ambient noise PSD is thus usually $(1/f^n)$ where noise has more power at lower frequencies and less power at higher frequencies [5]. Diurnal variability shows that the ship noise is greater at day than night but the biological noise on the contrary occurs more strongly at night than during the day. Shrimp noise is a form of biological noise which is likely to be found in waters less than about 55 meters deep and warmer than about 11 C°. It occurs extensively in tropical and subtropical coastal waters throughout the world. It has a diurnal variability being greater at night by 3 to 6 dB [6].

2. Underwater Acoustic Noise (UWAN)

Underwater acoustic noise (UWAN) has been under a thorough investigation and its characteristics in the ocean are well defined [6]. UWAN consists of four main components: turbulence, shipping, wind and thermal noise. Each component has a dominating impact at a

Received September 7, 2016; Revised December 27, 2016; Accepted January 26, 2017

different band of the frequency spectrum. Therefore, it is useful to define the PSD of each component through an empirical formula. The PSDs are found to be arithmetically proportional to frequency f [kHz] in [dB re μ Pa per Hz] [3, 7]. The power spectrum due to turbulence, shipping, wind and thermal noise are expressed as:

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

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

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

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

Where f is the frequency in kHz. The total noise power spectral density for a given frequency f [kHz] is then:

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

Figure 1 illustrates the empirical noise PSDs for different levels of shipping activities and with a wind speed of 3.6 m/sec (7 knots). Figure 2 shows the empirical noise power spectrum densities for different conditions of wind speed and with shipping activities (S=0.5). In general, the UWAN power spectrum is located in the area between the two curves $(1/f)$ and $(1/f^3)$. Moreover, it can be observed the turbulence noise is dominant in the frequency band (0.1Hz - 10Hz), while shipping activities are the major contributors to noise in a higher frequency band (10Hz - 200Hz). Shipping activities are usually weighted by a factor s which ranges from 0 to 1 which weighs the activity level from low to high activity respectively. The frequency band (0.2 kHz - 100 kHz) is conquered by surface motion, which is primarily affected by wind (w is the wind speed in m/s). For frequencies higher than (100 kHz) thermal noise is dominant. However, these noise sources are highly dependent on weather and other environmental factors.

The UWAN in shallow water has a greater variability in both time and location deep water. Therefore, it is more challenging to model or predict. Typical shallow-water environments cover water depths down to 200m while typical deep-water environments in all oceans are considered at depths exceeding 2000m [8]. In [5, 6], three major noise sources in shallow water environments namely wind noise, biological noise (especially noise created by snapping shrimp whose noise signature has a high amplitude and wide bandwidth) and shipping noise are identified. Furthermore, the UWAN power also decreases with the increasing depth as the distances between the surface, the shipping and wind noises become larger. In general, the UWAN has been shown to be 9 dB higher in shallow water compared to deep water [7].

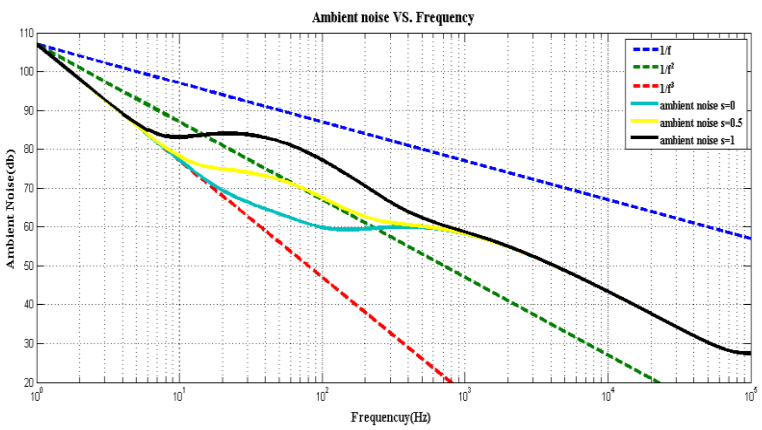


Figure 1. The noise PSDs in dB re μ Pa per Hz based on empirical formulae with wind speed 3.6 m/s (7 knots) and different Shipping noise is presented for high (s = 1), moderator (s = 0.5), light (s = 0) shipping activities

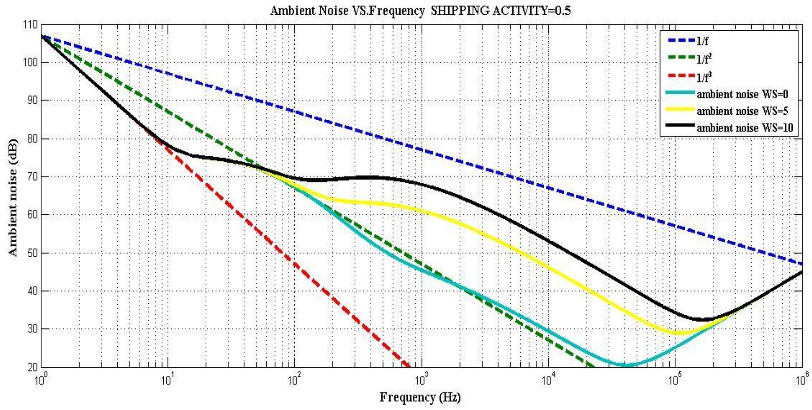


Figure 2. The noise PSDs in dB re μ Pa per Hz based on empirical formulae with Shipping activity S= 0.5 and for different wind speeds (w =0, 5 and 10 m/s)

3. Statistical Properties and Estimation

Unlike deterministic signals, random signals are best characterized by their statistical properties. Thus, the statistical properties such as autocorrelation function, PSD and pdf are demonstrated in this work.

3.1. Auto-Correlation Function

A random signal can be characterized in terms of the auto-correlation function. It shows the dependency of the signal at one-time t with respect to its time-shifted version by $(t+\tau)$. This is termed as auto-correlation function, which is also the cross-correlation of a signal with itself [9, 10] and is presented as follows:

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

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

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

The function depends on only relative time rather than the absolute t. In the normalized case, $0 \le r_{xx}(\tau) \le 1$, zero indicates no dependency and one refers to strong dependency [11].

3.2. Power Spectrum Density (PSD) and Estimation

The frequency representation of a random process is known as PSD while the estimation of the PSD is termed power spectrum estimation (PSE). In general, 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], [12-13].

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

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

Power spectrum in Equation (8) evaluated at f=0 yields:

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

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

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

Equation (10) implies that an autocorrelation function is integrable if $S_{xx}(0) < \infty$. On the other side, a PSD $S_{xx}(f)$is integrable when $r_{xx}(0) < \infty$ as indicated in Equation (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 $S_{xx}(0) = \infty$ [11].

There are five common non-parametric PSE [12]: periodogram, modified periodogram, Welch's method, Bartlett's method, and Blackman-Tukey method. Periodogram as a PSE is limited since it is a non-consistent PSE 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 most consistent PSE.

The Welch's method divides the time series data into overlapping segments and compute a modified periodogram of each segment, then averaging the PSD estimate is performed. The averaging effect introduced in this method decreases the variance in the PSD estimate with further reduction in variance by overlapping of segments.

If the signal is sampled at a normalized sampling frequency, the Welch method [12] 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.

3.3. Probability Density Function (pdf):

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 AWGN [9, 14]. It has shaped probability distribution function given by:

$$\rho_x(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \qquad (14)$$

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

Several publications have reported UWAN does not follow the normal distribution. Instead, it follows pdf with extended tails shape, reflecting an accentuated impulsive behavior due to the high incidence of large amplitude noise event [5]. The noise follows the alpha-stable PDF 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 modeling method is by means of empirical analysis of the noise samples obtained directly from the underwater environment [15].

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 Student's t pdf is expressed by [16]:

$$\rho_{x,v}(x,v) = \frac{\Gamma\left[{}^{(v+1)}/_{2}\right]}{\sqrt{\pi v}\,\Gamma({}^{v}/_{2})} \left(1 + \frac{(x-\mu_x)^2}{v}\right)^{-{}^{(v+1)}/_{2}} \qquad (15)$$

Where Γ(·) is the gamma function , v is the degree of freedom which controls the dispersion of the distribution and μ_x is the mean value. The lower the value of v, wider the tails of the pdf becomes and vice versa. The general Student's t distribution has the following properties [17]:

a) It has mean = 0 and the standard deviation is greater 1 for degrees of freedom, greater than 2 and it does not exist for 1 and 2 degrees of freedom. For sufficiently large values of the degree of freedom, the Student pdf converges to the Gaussian distribution.

b) The mean of ϵ is $E(x) = \mu_x$ for $v > 1$ and $E(x)$ does not exist for $v = 1$;

c) The variance of x is $var(x) = \frac{v}{v-2}$ for $v > 2$ and $var(x)$ does not exist for $v \leq 2$.

4. Results and Discussion

The UWAN samples were obtained directly from the underwater environment. Five different segments of samples were collected diurnally through the experiments conducted in shallow water at Tanjung Balau, Johor, Malaysia (Latitude 1° 35.87'N) and (Longitude 104° 15.793'E) on 22nd March 2014. The segments were received through a broadband hydrophone (7 Hz ~ 22 kHz) model DolphinEAR 100 Series, at different depths from 1 to 5 meters with sea floor at a depth of 10 meters. During the day time, the wind speed was about 8 Knots and the temperature at the surface of the sea about 26 C^0 while at night wind speed was about 11 Knots and the temperature at the surface of the sea about 27 C^0. The power spectrum is estimated using Welch modified periodogram technique and the data were analyzed for various depths. The setup for the power spectrum estimation is as follows: sampling frequency 8kHz, window type Hanning, 2048-point fast Fourier transform (FFT), FFT window size of 256 samples and 50% overlapping. Figure 3 shows the experiment site.

Figure 3. Experiment Test Site

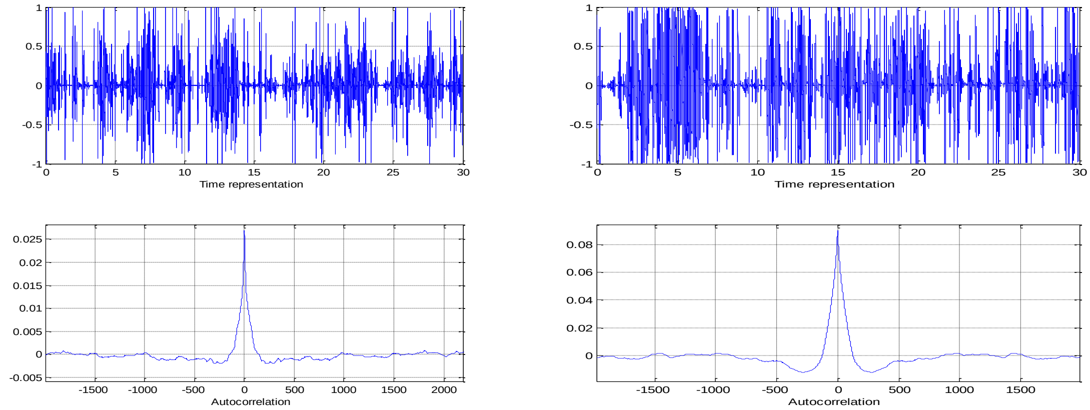
Figure 4. Field Trials Conducted at Tanjung Balau, Johor, Malaysia on the 22nd March 2014.

Figure 5 shows the time representation waveform and the autocorrelation function of the collected data during the day and night with depths of 3 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 the noise power at night is more than at day.

Figure 6 shows the PSE analyzed at different depths of 1 and 2 meters. It can be clearly seen that the noise power at night is greater than at the day by around (3-8dB). In general, the power spectrum estimates are located between $(1/f)$ and $(1/f^3)$.This confirms that the noise is not white, but colored.

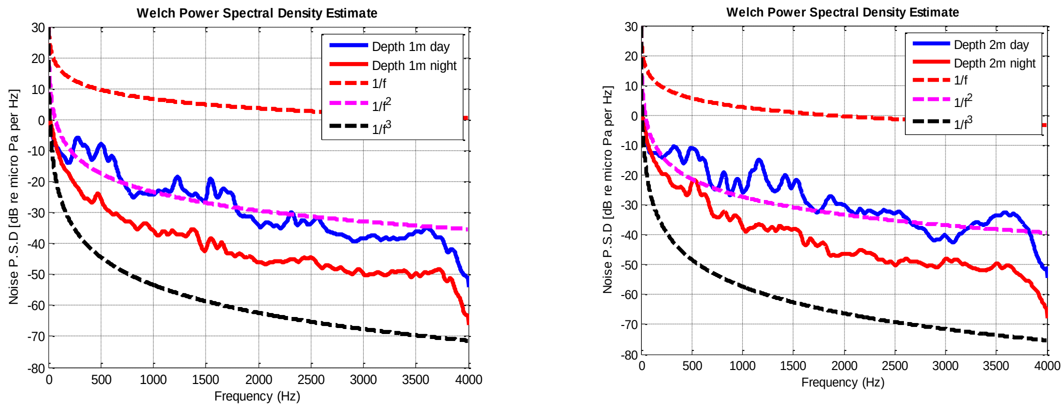
Figure 7 shows that the power spectral density (log scale) of the UWAN obtained from real field decays at a rate of approximately 15 dB/decade at day and 20 dB/decade at night. The result obtained differs from the result mentioned in reference [2] by -3 dB at day and +5dB at night, which the PSD of ambient noise decays at a rate of approximately 18 dB/decade.

Comparing the distributions obtained from the collected data with a Gaussian distribution and Student's t-distribution using distribution fitting tool in MATLAB, it can be clearly seen that the amplitude of the UWAN is distributed according to the Student's t-distribution as shown in Figure 8 and there is no difference in the amplitude distribution between the day and night.Therefore; the assumption of Gaussian distribution is not applicable in UWAN.



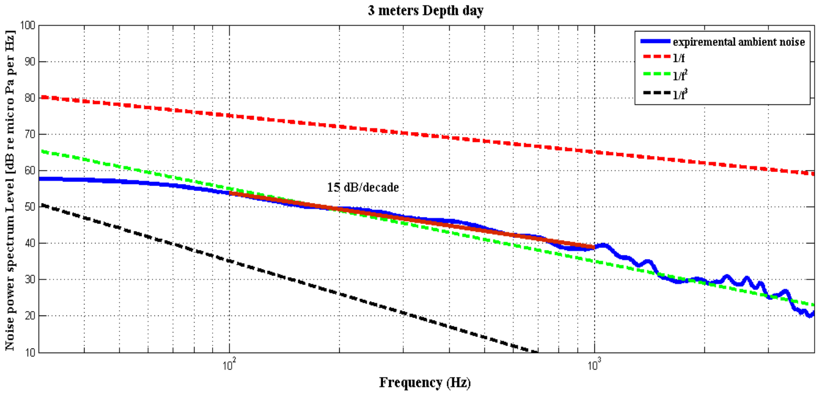
(a) Day (b) Night

Figure 5. Time Representation Waveform and Autocorrelation Function of the Underwater Acoustic Noise for the Day and Night at Depth 3 Meters

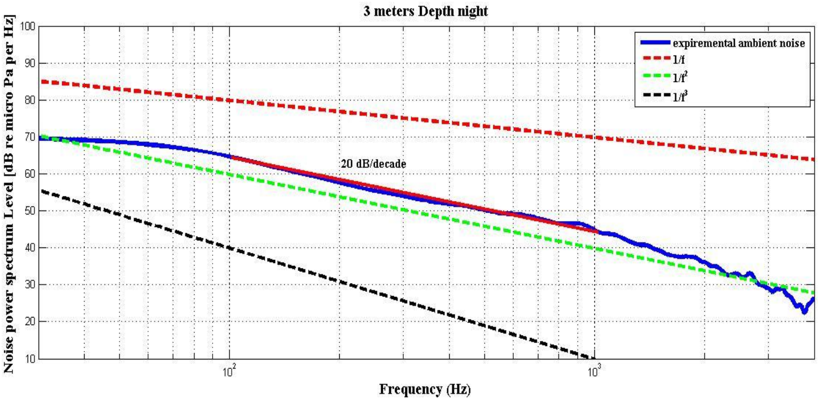


1 meter depth 2 meters depth

Figure 6. Welch PSD Estimate of UWAN for the Day and Night at Two Different Depths of 1 meter and 2 meters.

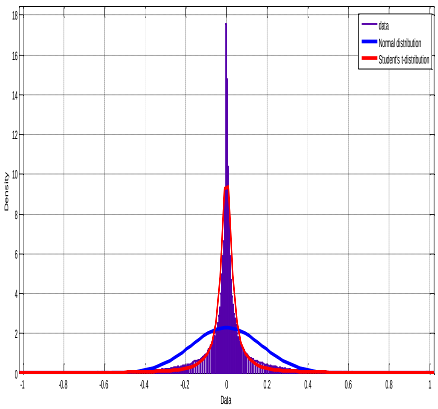


(a) Day

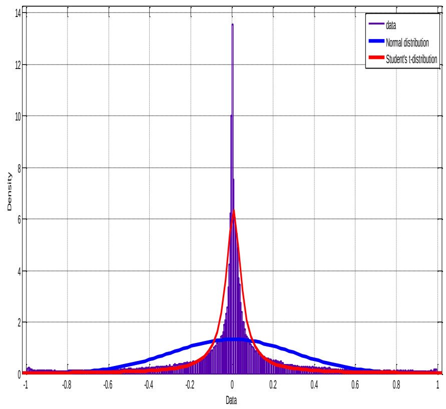


(b) Night

Figure 7. Welch Noise PSD estimate of UWAN for the day and night at depth 3 meters in logarithm scale



(a) day



(b) night

Figure 8. Comparison of the amplitude distribution of the UWAN with the Gaussian distribution and t-distribution for the day and night at depth 3 meters

5. Conclusion

UWAN characteristics of shallow waters in tropical seas have an accentuated impulsive behavior. The power spectral density is not a constant across the frequency range, and the correlation function is not a delta function. Thus, the UWAN with these characteristics is considered as colored noise. The noise amplitude distribution fitted with the student's t-distribution which is associated with the standard Gaussian distribution but presenting wider tails. Therefore, the UWAN does not follow the assumption of white noise nor a Gaussian distribution. The field trial also has shown that the noise power at night is higher than at the day by around (3-8dB).

Acknowledgements

The authors would like to thank the Universiti Teknologi Malaysia (UTM) and Ministry of Higher Education (MOHE) Malaysia for supporting this work.

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