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Annalakshmi Ganesan
SSN College of Engineering, Chennai, India.

Sakthivel Murugan Santhanam
SSN College of Engineering, Chennai, India., sakthivels@ssn.edu.in

Venugopal Padmanabhan
SSN College of Engineering, Chennai, India.

Swetha Vivekanandan
Musigma Bangalore, India.

Vaishali Selvaraj
Cognizant Technologies Solutions, Chennai, India.

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COHERENCE ANALYSIS OF AMBIENT NOISES IN SHALLOW WATER FOR UNDERWATER COMMUNICATION

Annalakshmi Ganesan[1], Sakthivel Murugan Santhanam[1], Venugopal Padmanabhan[1], Swetha Vivekanandan[2], and Vaishali Selvaraj[3]

Key words: ambient noise, coherence, shallow water, power spectral density, Bay of Bengal.

ABSTRACT

Ocean sounds play a major role in disturbances to the underwater transmission of acoustic signals. Because of the waveguide nature of shallow water, noise characteristics are highly variable. Similarly, because of the reflection of noise from the bottom surface and biological activities, the speed of sound varies substantially. Noise field characterisation is complex in shallow water regions. Ambient noise coherence analyses in shallow waters provide information about channel characteristics that could be helpful for underwater acoustic signal transmission. Ambient noise data were collected in the Bay of Bengal by considering factors including hydrophone depth, wind speed, noise type, sea depth, engine state, wind speed, temperature, biological noise, nonbiological noise, and wind direction. Finally, power spectral densities were plotted under various conditions for the collected noise data. For similar noise patterns, the observed variation in coherence was very low. A high variation in coherence was exhibited in data containing noise that arose from varying sources.

I. INTRODUCTION

Oceans are filled with sounds from various natural sources, such as wind, rain, breaking waves, and marine life, and artificial sources including ships, aircraft, military activities, and sonar (Gordon, 1962; and Ross, 1993). Efficient acoustic communication through an underwater channel can only be performed when various noises are analysed. Typically, in the presence of noise and interference, the signal-detection performance of communication is degraded. This problem becomes more complex when the noise distribution is unknown. These sounds play a major role in many areas, and knowledge about their statistical characteristics and spectral distribution is essential for understanding their impact on marine life as well as for regulating and controlling civilian and military activities. Coherence is one such statistic that can be used to study the relationship between two signals or data sets.

In shallow water regions, environmental characteristics continuously vary with time and location (Yang and Yoo, 1997). Wenz (1962) and Urick (1986) analysed the sources of ambient noise, including biological noise and nonbiological noise, as well as the average spectral characteristics of the observed noise. Interaction with the seabed substantially influences signal propagation in shallow regions, which also depends on the sound speed profile in shallow water regions. Cron et al. (1962) reported the spatial correlation functions between the pair of hydrophone to measure mean square noise output for various types of noise present in an ocean. Rudnick et al. (1967) reported the relative intensity of ambient sea noise in an octave band in three dimensional. Mean and variance calculation was carried for the 108 samples collected. Each mean was expressed as a departure from the output of the same beam for uncorrelated input. Desharnais et al. (1997; 1998) used three Lagrangian ambient noise drifters to analyse the coherence of shallow water noise at Scotian Shelf, Canada. The drifters were deployed at a depth of 15 m along with diverse equipment to measure the noise level in the frequency band between 50 Hz and 12.8 kHz. The result revealed ambient noise levels at 800 Hz with a wind speed of 10 m for the three coherence drifters over 2 days. During the measurement, the wind speed was approximately 5 m/s, local shipping was masked, and the real coherence and imaginary coherence were reduced. Norton (1996) and Kuperman (1987) demonstrated that the propagation of sound and attenuation of coherence components in the ocean are strongly affected by the sea surface and bottom roughness; this also influences the spatial characteristics of ambient noise. Whenever a strong refraction exists, the energy distribution and coherence are completely ignored, which results in a loss mechanism error in the signal.

Paper submitted 04/21/16; revised 10/07/16; accepted 01/13/17. Author for correspondence: S. Sakthivel Murugan (e-mail: sakthivels@ssn.edu.in).
[1] *SSN College of Engineering, Chennai, India.*
[2] *Musigma Bangalore, India.*
[3] *Cognizant Technologies Solutions, Chennai, India.*

Individual estimates of coherence for different wind speeds conducted by Sanjana et al. (2009) clearly exhibited changes in the coherence pattern and variance in the measurement. Vertical linear-array hydrophones were deployed in shallow water regions at a depth of 30 m. Samples were taken every 30 s at a frequency of 25 kHz. The ambient noise data were gathered at wind speeds of 2.7-9.6 m/s. Coherence analysis was performed by varying the separation between the receivers. If the spacing between two receivers was small, no coherence was detected and the surface dominated the other noises. Moreover, if the wind speed increased, the coherence of signal decreased as the spacing between the receivers increased. Buckingham (1980) conducted a study at the Bay of Bengal and proposed a systematic model of surface-generated noise in shallow water regions. Persistence was used to examine the vertical coherence of the noise at frequencies below 1 kHz. Harrison (1996) developed a noise model with a range-dependent environment. Deane et al. (1997) evaluated the vertical coherence for ambient noise at two different sites with a fluid seabed. They concluded that the vertical coherence of wind-generated noise was unaffected by the nature of the source, but it was determined by the source depth and seabed properties. They also observed that the seabed properties affected not only the noise level, but also its spatial structure. A model of vertical noise coherence proposed by Chapman et al. (1997) determines that noise levels due to wind do not substantially influence coherence. This is a normalised measurement, and the sound speed profile of the water column directly influences the spatial distribution of the noise and thus coherence. The model facilitates inferring seabed properties from coherence measurements. The dependencies of ambient noise on the reflective properties of the seabed were presented by Carbone et al. (1997) and were subsequently used to invert compressional and shear wave speeds by using the vertical noise coherence. Ambient noise measurements carried out in Indian seas have demonstrated that the frequency spectra of rain noise can be used to detect the rainfall rate. The spatial structures of sensors related to rain noise have been reflected in the vertical coherence of ambient noise. Douglas (2008) and Hildebrand (2009) analysed anthropogenic noise generated by various ocean sources. Some sources of ambient noise, such as exploration, seismic exploration, sonar, and acoustic devices, produce sound intentionally. In addition, typical anthropogenic noise sources have been explained in detail. Preisig (2005) briefly discussed the effect of scattering, multipath propagation, absorption, spreading loss, and ambient noise. There is no single-channel model for acoustic propagation characteristics for underwater environments. Bannister (1979) examined various factors such as depth, frequency, wind dependency, and the spatial deviation of ambient noise. The results were compared with existing findings, and they showed that the standard deviation increased with the number of ships. Kewley (1990) examined vertical noise directionality in the Northern Hemisphere for various sources of ambient noise. By recasting the various results in a similar manner, they achieved a reliable comparison. The source level for wind-dependent noise was realised on the basis of several collected data. Knudsen (1948) documented winddependent ambient noise and the average spectrum corresponding to the sea level. The seasonal change in wind speed also influenced the noise level in the ocean over all frequencies less than 200 Hz. The wind speed was low in summer and high in winter. Hamson (1997) reviewed ambient models for shipping and wind sources. The noise sources were described in terms of both horizontal and vertical directionalities. Ingenito (1989) reported that the wind dominance in shallow water regions was low (approximately 2 dB) at a wind speed of 7 m/s. The wind noise spectrum was measured for the same wind speed. The results indicated that signal propagation depends on the season, ocean depth, and seabed composition. Murugan et al. (2014) collected various ambient noise data reporting frequency spectra ranging from 100 Hz to 10 KHz at various depths using 6 array element hydrophone system. The data for various sources of noises were collected at different depths of 5 m, 10 m and 15 m at Bay of Bengal. Ashokan et al. (2015) had carried coherence analysis for sea surface noise and rain noise in Bay of Bengal and Arabian Sea. It is observed that the frequency spectra generated due to rain fall can be used to detect the rain rate. The Rain noise is considered as a natural source of ambient noise.

II. FIELD MEASUREMENT NOISE ANALYSIS AND CLASSIFICATION

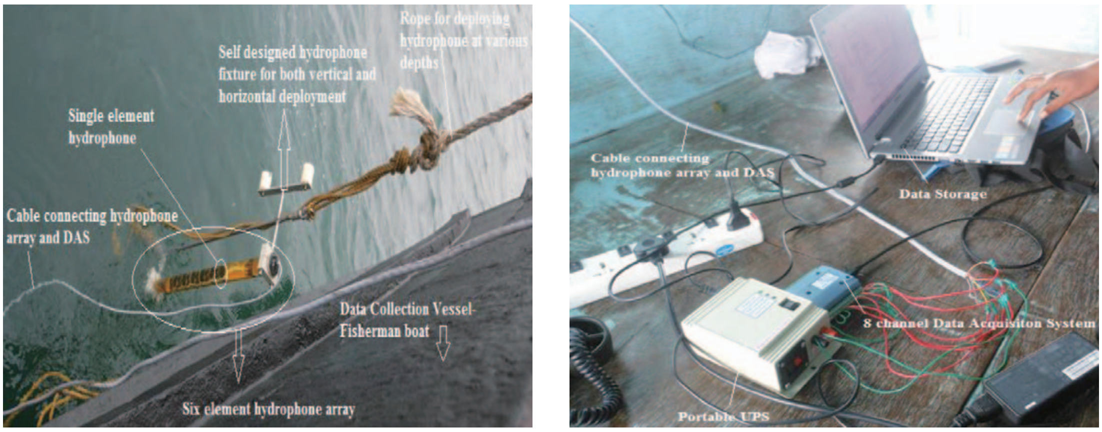
Several ambient noise data sets were collected from two different sites in the Bay of Bengal: Ennore and Kasimedu, Chennai, India. The data collection was conducted using a data logger comprising a six-element hydrophone receiver array with a length of 1 m and an interelement spacing of 7.5 cm and equipped with a preamplifier. The sensitivity of the hydrophones is -170 dB at frequencies of up to 25 kHz. The data were collected between 8:00 and 14:00 hours over 4 days. The array was deployed in shallow water regions at various depths ranging from the sea surface to 15 m. Acquired data were filtered and digitised using a portable data acquisition system (DAS) with a 12-bit resolution and a sampling rate of 25,000 samples per second. The following equipment was also used:

1. Wind meter to record the wind speed during data collection;
2. Temperature sensors to monitor the temperature during data collection;
3. Portable uninterruptable power supply for power back up during data collection:
4. Power supply unit to power all the systems used for data collection;
5. External storage device to record the ambient noise data collected for analysis;
6. GPS to position the locations of data collected at various times;
7. Echo sounder to determine the depth of the sea for data collection at various depths (the depth of the sea in fathoms at a particular location was recorded by the meter).

Table 1. Real-time ambient noise data collection and classifications.

Location	Hydrophone depth (m)	Sea depth (m)	Engine state	Echo sounder	Temp. (°C)	Time (hrs)	Types of Noise
13.09007 N 80.19523 E	5	15	OFF	ON	41.08	13.15-13.25	wind
	10	15	OFF	ON	41.08	12.55-13.05	Movement and Aircraft
13.09095 N 80.19713 E	3	20	OFF	ON	33	11.00-12.00	wind
	5	20	OFF	ON	33	12.30-13.45	wind
13.06856 N 80.20360 E	15	25	OFF	ON	30.00	10.15-10.25	Helicopter

Location 1: Data were recorded at 13.0907 N and 80.19523 E, where the sea depth was 15 m. The hydrophone array was deployed at depths of 10 and 5 m in both vertical and horizontal positions. The wind speed ranged from 1 to 5 m/s. The engine state was OFF.
Location 2: Data were collected near a shipping area at 13.09095 N and 80.19713 E, where the sea depth was 20 m. The hydrophone array was deployed at depths of 3, 4, and 5 m in both vertical and horizontal positions. Data were also collected at the sea surface. The wind speed ranged from 1 to 6 m/s. Unavoidable noise from ship horns and aircraft was also recorded occasionally.
Location 3: Data were recorded at 13.06856 N and 80.20360 E, where the sea depth was 25 m. The hydrophone array was deployed at a depth of 15 m and at the surface. The wind speed ranged from 2 to 5 m/s. Unavoidable helicopter noise was also recorded.



(a) (b)

Fig. 2. (a) Hydrophone array deployment; (b) DAS and storage.

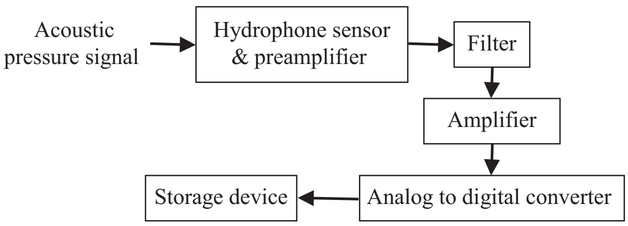


Fig. 1. Block diagram of a simple DAS.

Fig. 1 depicts a block diagram of a simple DAS. Data were recorded using a wideband, two-channel DAS interfaced with a laptop. A digital signal processing-based system with an inbuilt antialiasing filter and a 12-bit resolution card with a sampling capacity of 25 kHz and a 1 MB buffer memory were employed. Real-time pressure data acquired from the hydrophone sensor were amplified, filtered, and stored in the storage device for analysis.

The real-time data collection systems were deployed in Chennai, the Bay of Bengal, (Fig. 2(a)). The data collection systems include two calibrated hydrophones suspended from the measurement platform by a rope fitted on a heavy fixture of 6 ft, which was suspended from the side of the boat at various depths ranging from 5 to 15 m from the sea surface. Both hydrophones were spatially separated, with a horizontal difference of 40 cm and vertical separation of 280 cm. Fig. 2(b) displays the DAS system, which was connected to the laptop to collect and store the ambient noise data with the help of the hydrophones. During data collection, all machinery on the boat was switched off to avoid self-noise. The wind speeds ranged from 0.7 to 8.0 m/s and were simultaneously measured along with the other data. Collected data were classified in terms of location, wind speed, hydrophone deployment depth, and the type of noise present in the region.

Data collected on different days were classified in terms of location, wind speed, hydrophone deployment depth, sea depth, and the type of noise recorded. Table 1 presents some of the sample data classification.

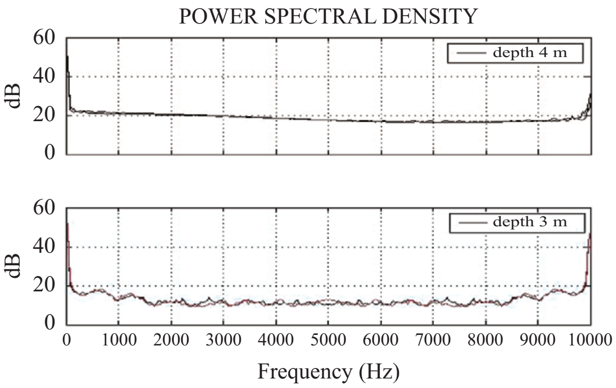


Fig. 3. PSD of ambient noise collected at 4 and 3 m.

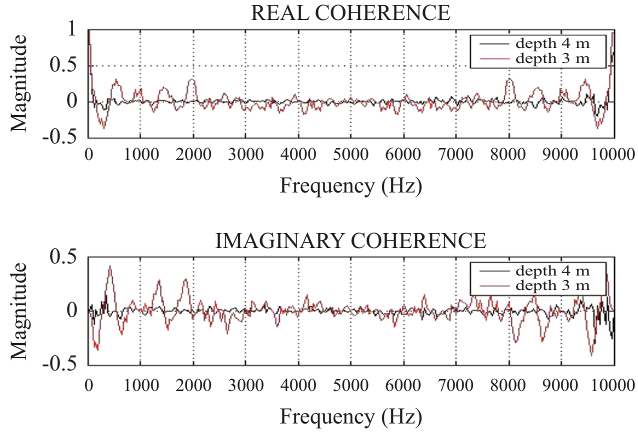


Fig. 4. Coherence analysis of ambient noise collected at 4 and 3 m.

1. Ambient Noise Coherence

Nolte et al. (2004) explains the coherency between two channels is a measure of the linear relationship of the channels at a specific frequency. It is a statistic that can be used to examine the relationship between two signals or data sets. Coherence between two signals is a real valued function that is defined as follows:

$$\Gamma_{12} \frac{\overline{S_{12}}}{\sqrt{\overline{S_{11}}} * \sqrt{\overline{S_{22}}}}$$

where $\overline{S_{12}}$ is a cross-spectral density function, $\overline{S_{11}}$ and $\overline{S_{22}}$ are the autospectral densities of signals 1 and 2, respectively, and Γ_{12} is the coherence of two signals and satisfies the condition $0 \le \Gamma_{12} \le 1$. If the two signals are highly correlated, the coherence is close to 1. The more the signal patterns differ, the higher the variance in coherence and the lower its magnitude are.

III. RESULTS AND DISCUSSION

Coherence analysis of ambient noise data collected from the Bay of Bengal was conducted for eight different cases related to ambient noise collected at depths ranging from the surface to 3, 4, 5, and 10 m. Because the data collection vessel was drifting, care was taken to avoid self-noise caused by the sound of the vessel. Steps were also taken to ensure a fair coherence evaluation process.

Case (i): Coherence Analysis of Data Collected at Depths between 3 and 4 m

Fig. 3 presents the power spectral density (PSD) of ambient noise collected at 4 and 3 m. This analysis was performed to study the variation in ambient noise present at a depth difference of 1 m. At 3 m, this study determined a noticeable variation in the noise level compared with that at 4 m throughout the spectrum. The noise level at 3 m was lower than that at 4 m.

The real component of coherence in Fig. 4 clearly indicates that the variance in coherence was feeble at 4 m, whereas the coherence had a high degree of asymmetry in the horizontal direction at 3 m. This was due to the absence of prominent noise sources at 4 m.

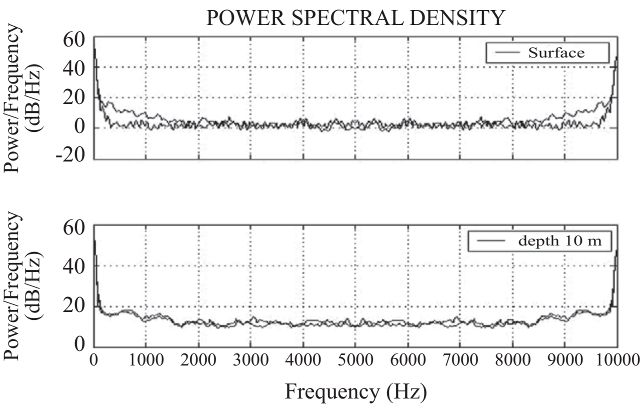


Fig. 5. PSD of ambient noise collected at the surface and at 10 m.

Case (ii): Coherence Analysis between Data from the Surface and 10 m

Fig. 5 depicts the PSD of ambient noise collected at the surface and at a depth of 10 m. Because the surface is highly prone to noise in the surroundings, this study identified a visible variation in the the collected data. The noise level ranged from -2 to 20 dB over frequencies from 2 to 8 kHz. The noise for the data collected at 10 m varied between 10 and 20 dB throughout the frequency range.

Fig. 6 shows a high amplitude of oscillation about zero for the real and imaginary components of coherence for noise at a depth of 10 m at frequencies lower than 2 kHz and higher than 8 kHz. This variation gradually dampened between 2 and 8 kHz. The variance in coherence for noise collected at the surface was uniform throughout the frequency range.

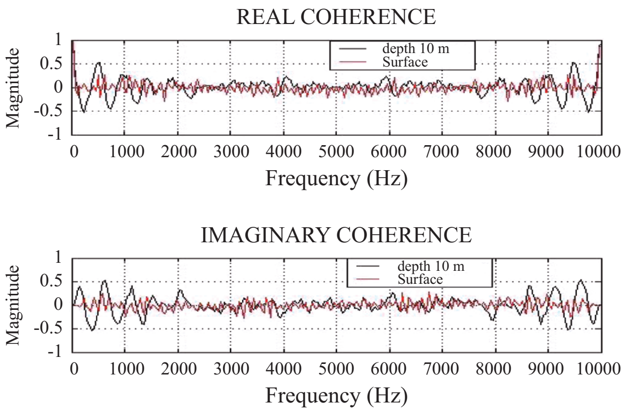


Fig. 6. Coherence analysis of ambient noise at the surface and at 10 m.

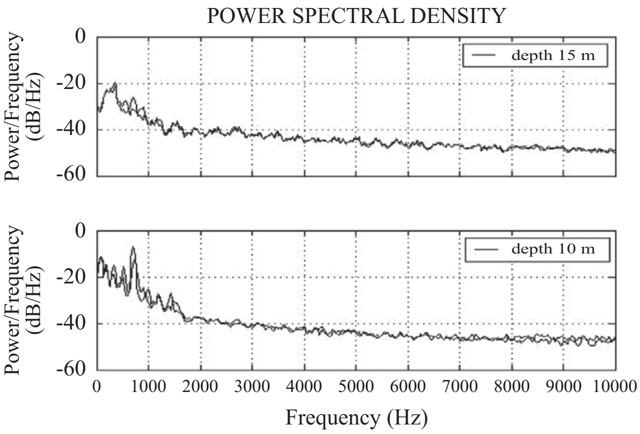


Fig. 7. PSD of ambient noise at 15 m.

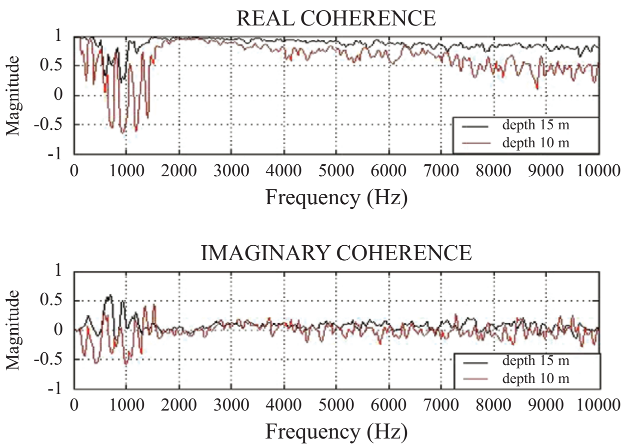


Fig. 8. Coherence analysis of ambient noise at 10 and 15 m.

Case (iii): Coherence Analysis of Data Collected at Depths between 15 and 10 m

Fig. 7 displays a dominant peak in the PSD plot for ambient noise collected at 10 m, but the data from a depth of 15 m reveal no such peak. This may be due to the absence of some biological ambient noise sources that were present at 10 m.

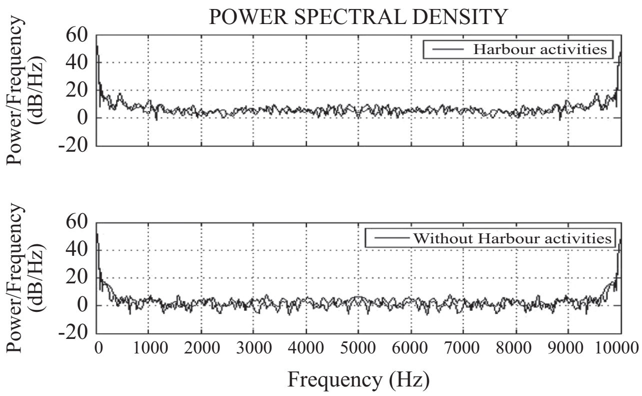


Fig. 9. PSD of harbour noise.

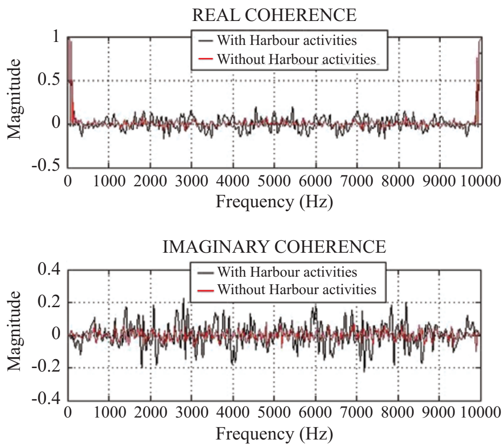


Fig. 10. Coherence analysis with and without manmade harbour noise.

The peak observed in the noise level in Fig. 8 demonstrates a high variance in the coherence below 2 kHz. The real coherence was high between 2 and 3 kHz. Above 3 kHz, the coherence at 15 m was higher than that at 10 m. This was due to the non-homogeneous nature of the sea surface, which includes many noise sources.

Case (iv): Coherence of Harbour Noise

Fig. 9 shows the PSD of harbour noise collected in the presence and absence of harbour activities. In the absence of harbour activities, the noise level ranged between -10 and 10 dB. In the presence of harbour activities, the noise level was positive. An increase in noise level was also observed.

Fig. 10 shows the real and imaginary components of the vertical coherence of noise data taken in the presence and absence of harbour activities. Because of the presence of asymmetric noise components in the data collected in the presence of harbour activities, a higher variance in coherence was observed.

Case (v): Coherence Analysis of Boat and Generator Noise

Fig. 11 shows the PSD of generator noise and boat noise. Two data sets collected at different times were considered for

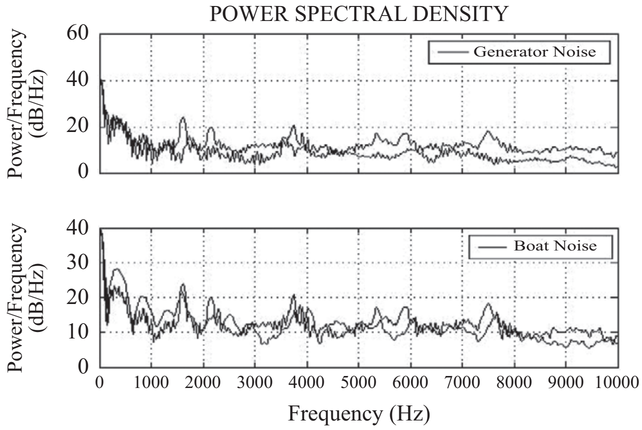


Fig. 11. PSD of generator noise and boat noise.

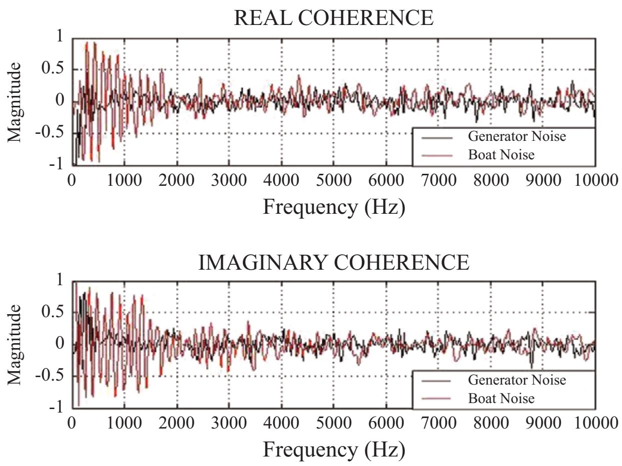


Fig. 12. Coherence analysis of boat and generator noise.

each case. Because the channel is inherently dynamic, a variation was visible between the generator noise data sets. At frequencies lower than 1.5 kHz, no considerable variation was observed. As the frequency increased, the observed variation increased. The variation in the PSD of boat noise was less than the variation in that for generator noise.

Fig. 12 shows the real and imaginary parts of the vertical coherence for boat noise and generator noise. Approaching the boat from a distance contributed to a high variance in real coherence up to a frequency of 2 kHz, and its effect gradually decreased but was still higher than the variance in coherence caused by generator noise.

Case (vi): Coherence Analysis of Generator Noise with and without Boat Noise

Fig. 13 presents the PSD of generator noise with and without boat noise. Two data sets collected at different times were considered for each case. Because the channel is inherently dynamic, a visible variation was observed in the two noise data sets. At frequencies lower than 1.5 kHz, no considerable variation was observed between the two data sets. As the frequency increased, the variation in the PSD plots was observed.

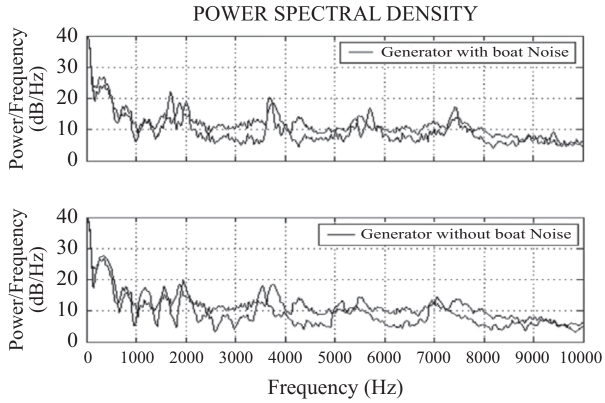


Fig. 13. PSD of generator noise with and without boat noise.

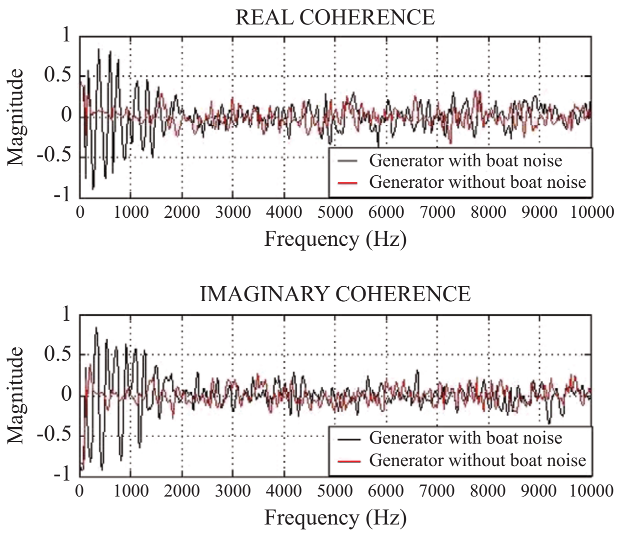


Fig. 14. Coherence analysis of generator noise with and without surround boats noise.

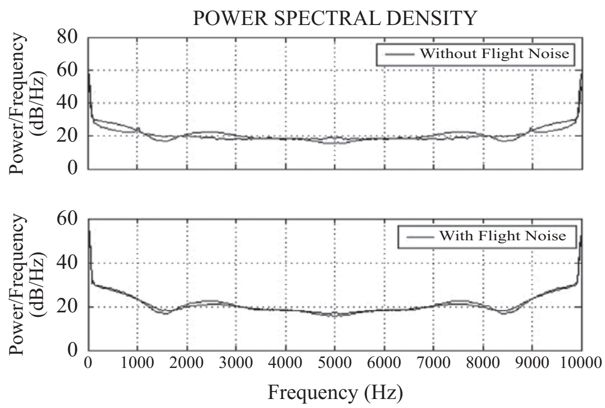


Fig. 15. PSD of ambient noise with and without aircraft noise.

Fig. 14 illustrates the real and imaginary components of the vertical coherence of generator noise with and without boat noise. In the presence of boat noise, the variance in real coherence was

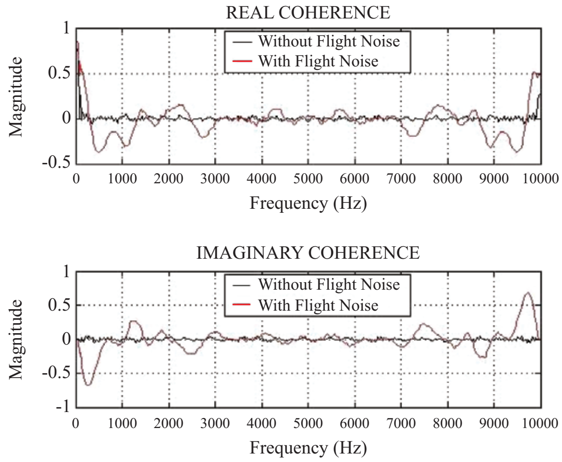


Fig. 16. Coherence analysis of ambient noise with and without flight noise above sea level.

high at frequencies lower than 2 kHz, whereas in the absence of boat noise, the variance in real coherence was negligible. This indicates that the coherence of the channel in the presence of both generator noise and boat noise was greatly influenced by boat noise, which dominated the observed generator noise.

Case (vii): Coherence Analysis of Ambient Noise with and without Aircraft Noise

Fig. 15 presents the PSD of data collected in the absence of aircraft and during the crossing of an aircraft just above the sea. The hydrophones were horizontally deployed at a depth of 5 m in both cases. The variation in power intensity was feeble because the hydrophones were deployed at 5 m, where the density of water reduces the effect of aircraft noise.

Fig. 16 shows the real and imaginary components of the vertical coherence of noise data with and without aircraft noise. In the presence of aircraft noise, the coherence exhibited high variance in the horizontal direction. This result was similar to that of the coherence of harbour noise.

Case (viii): Coherence Analysis for Rain and Drizzle Noise

Fig. 17 displays the PSD of rain noise and drizzle noise. The PSD of drizzle noise was more stable than that of rain noise. Noise level fluctuations were higher for rain noise than for drizzle noise.

Fig. 18 illustrates the real and imaginary components of the vertical coherence of rain noise and drizzle noise. As rain noise increased, the observed coherence decreased. The disturbances contributed by rain noise to a signal being transmitted are higher than those contributed by slight rain or drizzle. Hence, the variance in coherence increased with rain noise.

IV. CONCLUSION

This study investigated the coherence of ambient noise collected at two different locations in the Bay of Bengal under various conditions and at various depths and wind speeds. Coherence was identified to exhibit high variance for noise recorded at the surface. As the depth of hydrophone deployment increased, the effect of surface noise decreased. Real and imaginary components of vertical coherence were analysed under various conditions for the collected ambient noise data with different wind speeds, hydrophone deployment depths, and types of ambient noise. In an ideal situation, vertical coherence should be stable over a wide range of frequencies. Noise data collected for various wind speeds were categorised into different types, namely ship, boat, and aircraft. Real and imaginary components of coherence were computed for different noise data sets.

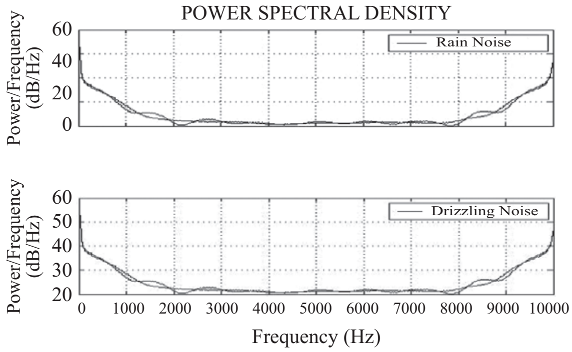


Fig. 17. PSD of rain noise and drizzle noise.

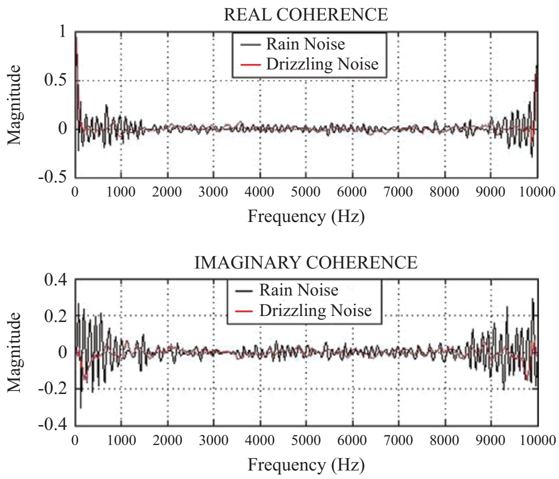


Fig. 18. Coherence analyses of rain and drizzle noise.

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