Seabed characteristics from ambient noise at three shallow water sites in Northern Indian Ocean

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Abstract: Ambient noise measurements at three sites along the Indian continental shelf, with different water column and seabed, are analyzed to derive vertical directionality and further estimation of seabed characteristics. Directionality pattern is interpreted using features in the sound speed profiles, in terms of noise notch, surface duct, surface bottom reflections, direct arrivals, and high bottom loss arrivals. Reflection loss estimated from the field directionality is seen to be the same for a particular site and gives an estimate of the sea bottom. Seabed characteristics such as critical angle and reflection coefficient from field directionality correlate well with theoretical estimation using ground truths.

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1. Introduction

In shallow water, the ambient noise (AN) field depends on the noise source distribution as well as the environmental parameters such as bathymetry, sound speed profile (SSP), and seabed properties. In a waveguide bounded by sea surface and seabed, multipath propagation prevails and the spatial structure of the noise field is largely dependent on the seabed. Thus, it is possible to deduce the bottom properties from the noise field, knowing the water column properties and sea surface conditions. Considerable efforts have been made in this field using passive as well as active techniques. Passive measurements have been widely used for estimating geoacoustic parameters directly from the measured noise field such as coherence and directionality,[1–4] as well as through matched field inversion using forward propagation models and optimization algorithms for searching the model parameter space.[5,6]

Active techniques have been employed in geoacoustic inversion, using sources and receivers. Geoacoustic inversion of fine grained sediments using angle of intromission was carried out by Holland,[7] and results were seen to compare favorably with ground truth data. Geoacoustic inversion using noise field spatial coherence from low frequency air gun sources had been carried out by Jiang and Chapman[8] and the uncertainty of geoacoustic parameter estimates had been quantified. A time domain matched beam processing was also attempted by Jiang *et al.*,[9] using broadband data from a long range propagation experiment, and the estimates agree well with ground truth information. Yang *et al.*,[10] used a source and a ship towed line array system for estimating bottom properties and sub-bottom profiling. Yang *et al.*,[11] also carried out mid-frequency geoacoustic inversion in the band 2–5 kHz from bottom loss measurements using a towed source and a fixed array.

Harrison and Simons[2] have developed a simple method for deriving the geoacoustic parameters of the seabed using reflection loss (RL). RL is estimated from vertical array measurements of AN, directly from the upward and downward looking beam ratio. Siderius and Harrison[12] inverted seabed properties using the same approach, from RL for short arrays. In the present work, passive vertical array measurements of AN at three different shallow water sites are used for estimating seabed characteristics in terms of critical angle and RL estimates

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using Harrison's method.[2,12] The three sites exhibit different sea bottom conditions and varying SSP. The vertical directionality pattern at the site is described in relation to sound propagation for the specific SSP. This study is the first such effort in seabed characterization from passive AN measurements for warm shallow tropical Indian Ocean region.

2. Acoustic measurements

A vertical linear array of 12 hydrophones along with data acquisition modules were deployed at 2 sites in the Bay of Bengal (off Cuddalore and Visakhapatnam) and 1 site in the Arabian Sea (off Cochin) for time series measurements [Fig. 1(a)]. The data sets considered for this study are during: September 21, 2010 (off Cuddalore), May 23, 2011 (off Cochin), and December 10, 2011 (off Visakhapatnam). The water depth varied between 30 m and 33 m, with the array of sensors positioned at the mid-water column. The omnidirectional hydrophones in the array, with bandwidth 0.1–8 kHz, acquire noise data with simultaneous sampling of 50 kHz, for duration of 30 s every 3 h. The site is also surveyed for sound speed profiles and sea bed properties. Grab samples of the surface sediment were collected in and around the site and further subjected to sieve analysis/particle size analysis for further characterization.

The SSP measured at the sites is given in Fig. 1(b). The SSP exhibits varying structure for each site, a nearly iso-velocity profile off Cuddalore, an upward refracting profile off Visakhapatnam, and a downward refracting profile off Cochin. For evaluating the complex environment, the features in the SSP is investigated in terms of the value at the receiver c_r, maximum value above the receiver c_u, maximum value in the entire water column $c_{\max}$, and value at the sea bottom c_c, as per the general rule of thumb by Harrison.[13] These translate into angles, $\cos\theta_0 = c_r/c_u$; $\cos\theta_1 = c_r/c_{\max}$; $\cos\theta_2 = c_r/c_c$. If $c_u \geq c_r$, there is a possibility of a noise notch (NN) in the directionality pattern, a range of angles that is surface noise free. If $c_{\max} > c_u$, there may be a surface duct (SD) with upward refraction. If $c_c > c_{\max}$, there may be low loss surface and bottom reflected paths. Above c_c, there will be direct paths and high bottom loss paths.[13]

The angles θ_0, θ_1, and θ_2 calculated from the sound speed in the water column and seabed are given in Table 1 for the three sites. The sediment samples collected at the sites were subjected to grain size analysis to estimate sound speed in the seabed. Mean grain size is determined in the laboratory by grain size analysis using sieving to separate the sand fraction. The hydrometer method is used for size analysis of silt and clay fraction. From the percentage of sand, silt, and clay fractions, Hamilton's model[14] values for continental shelf and slope environment is used to arrive at the sound speed

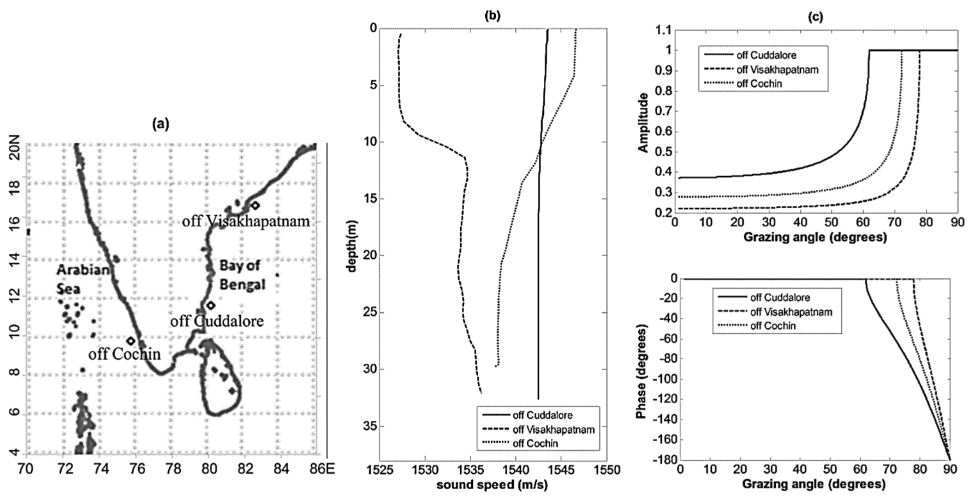

Fig. 1. (a) Acoustic measurement sites, off Cuddalore and off Visakhapatnam (east coast); off Cochin (west coast), (b) SSP in the water column at the three sites, and (c) theoretical reflection coefficient for zero loss at the three sites.

Table 1. Sound speed characteristics at the sites for angle mapping.

Site	Sound speed in water column (m/s)				Angles (degree)			Wind speed (m/s)
	Receiver (c_r)	Top (c_u)	Bottom (c_b)	Maximum (c_{max})	θ_0	θ_1	θ_2	
Off Cuddalore	1542.5	1543.5	1542	1543.5	2.06	2.06	28.12	2.0–3.0
Off Visakhapatnam	1534	1527	1536	1536	0	2.92	12.12	3.3–4.4
Off Cochin	1540	1547	1538	1547	5.45	5.45	17.76	2.6–4.0

values. The sound speed values are 1749 m/s, 1569 m/s, and 1615 m/s for Cuddalore, Visakhapatnam, and Cochin, respectively.

The results from Table 1 show the presence of a narrow NN off Cuddalore and Cochin ($\theta_0 = 2.06°$ and $\theta_0 = 5.45°$, respectively) and the presence of SD off Visakhapatnam ($\theta_1 = 2.92°$) with an upward refracting profile. In a SD, θ_1 is the steepest ray angle at the receiver sustainable by the duct. Surface/bottom reflections fall within $\pm 28.12°$, $\pm 12.12°$, and $\pm 17.76°$ for Cuddalore, Visakhapatnam, and Cochin, respectively [Fig. 1(c)]. Beyond this, sound arrives as direct paths at the surface and high bottom loss paths at the bottom.

3. Estimation of geoacoustic properties

The vertical directionality of AN derived from an array of hydrophones can be used for estimating geoacoustic properties. The method involves beamforming and separating the up and down going beams.[2] The ratio of upward looking beam to downward looking beam produces an estimate of RL. The ratio is the power reflection coefficient, a function of angle and frequency.[2] Thus, bottom power reflection coefficient $R_b = U/D$, where U is the upward flux and D is the downward flux. A receiver array deployed in an ocean waveguide can be used to measure U and D and further deduce R_b. At higher frequencies and in ray based modeling, RL estimate is seen to be more useful than conventional geoacoustic properties. As given in Harrison and Simons[2] knowing the sound speed profile at the site, it is possible to map the beam ratio from the angle measured (by beamforming) at the receiver, θ_r, to the angle at the sea bed, θ_b. By Snell's law

$$\theta_b = a\cos((c_b/c_r)\cos(\theta_r)), \tag{1}$$

$$\text{Reflection coefficient } R = \frac{1 - \dfrac{\rho_w c_w}{\rho_b c_b}\dfrac{\cos\theta_b}{\cos\theta_w}}{1 + \dfrac{\rho_w c_w}{\rho_b c_b}\dfrac{\cos\theta_b}{\cos\theta_w}}. \tag{2}$$

Knowing the reflection coefficient and water column sound speed, water column density etc., the sediment properties can be deduced.[15] RL or bottom loss (BL) is defined in decibels as $BL = -10\log|R|^2$.

4. Results and discussion

AN recorded at three different sites with water depths varying from 30–33 m are taken for seabed characterization studies. At all the sites, wind speed, rainfall, SSP, and sediment grab samples have been taken to understand the boundary conditions and volume properties in the shallow wave guide. Wind and rain interacting with sea surface produce a sheet source that spread in different angular directions. Sound from these sources travel to the bottom and get reflected/absorbed depending on the material there. The reflected rays contribute to the bottom sources. Hence, the noise received at an array has direct surface arrivals, reflected bottom arrivals, distant noise along the horizontal, and contribution from other intermittent sources. The noise directionality or the resultant arrival of noise in different directions is temporally and spatially varying depending on the sources at the surface and in the water column. As mentioned in Sec. 3, RL can be estimated from directionality, which is the ratio of upward arrivals and downward arrivals. This ratio is found to be the same for a particular site over the period of measurement, and gives an estimate of sea bottom. RL at three sites in shallow North Indian Ocean is discussed here.

The array considered here is a short array, with vertical aperture of 1.65 m. Generally, as vertical aperture decreases, the band of operation shifts toward higher frequencies. The spacing in the array is 0.15 m, corresponding to a half wavelength for 5 kHz. When hydrophone spacing is larger than half a wavelength, grating lobes are introduced that erroneously mix the up and down going beams, hence estimates >5 kHz are not considered. Furthermore, shipping which falls in the low frequency end, <2 kHz, can interfere with the beamformed output and the RL estimate will be affected. Hence, 2–5 kHz is considered for computing the RL and estimating the bottom properties.

4.1 Off Cuddalore—Bay of Bengal

The water depth is 33 m with bottom sediment of poorly graded fine sand. The SSP is near isovelocity with variation of about 1 m/s only in the upper layers during the course of the day. The critical angle estimated from water column and sea bottom sound speed is calculated as $\theta_c = \arccos(1542.5/1749) = 28.12°$. The continental shelf gradient is ≈0.09°.

The site is characterized by dominant surface bottom reflections that propagate in the water column due to the near isovelocity profile. The bathymetry is nearly flat and ensures better propagation. The directionality pattern [Fig. 2(a)] exhibits horizontal distribution, and the minute notch as estimated in Sec. 2 for the site is not seen in the measurements. This is possibly due to the array beamwidth at 3 dB of 8.4° at design frequency of 5 kHz, which is insufficient to detect the narrow notch of 2.06°. A flat topped angular distribution is seen under these conditions. Since the sea bottom is hard, the bottom reflections will be intense. For a near isovelocity profile and hard bottom case, the distant noise could completely remove the null in the noise vertical directionality. The broadening of the lobes in the low frequency end in the directionality pattern is due to poor angular resolution.

The up to down ratio, which gives the RL, is seen in Fig. 2(b). Angles have been corrected from that at the receiver to that at the seabed according to sound speed.[2] Up to critical angle, the loss is minimum and there are two interference lobes beyond which is the expected pattern for a high sound speed bottom as explained by Harrison.[2] Low loss at low frequency end is due to small angular resolution, say up to 1.5 kHz, which degrades the up to down beam ratio. The array beamwidths at 3 dB points for 5 kHz, 4 kHz, 3 kHz, 2 kHz, and 1.5 kHz are 8.4°, 10.4°, 14.14°, 21.2°, and 28.4°, respectively.

4.2 Off Visakhapatnam—Bay of Bengal

The water depth is 32 m with bottom sediment of clayey silt. The SSP is upward refracting with a gradient of 8 m/s, and this is due to winter inversion as a result of surface cooling causing a weak thermal gradient. The critical angle at the site is estimated to be $\theta_c = \arccos(1534/1569) = 12.12°$. The continental shelf gradient is ≈0.3°.

Upward refraction at the site leads to a SD and surface bottom reflections. NN is absent because there is no maximum sound speed above the array [Fig. 3(a)]. The range dependent environment with variable bathymetry gives rise to diversion of steeply reflected paths into the sound channel.[16] Effect of SD is the enhanced beam intensities at lower angles. Due to bottom loss, and the sloping environment, the distant noise contributes little to the noise beam power. The secondary hump in the directionality pattern corresponds to low loss bottom reflected paths. The kink gives the effective critical angle. In the RL figure [Fig. 3(b)], beyond the critical angle, fine fringes are seen at low frequencies and a coarse fringe above 3 kHz. The fine fringes at the low frequency end may be caused due to a thick layer, since low frequencies are not affected by thin layers. The coarse fringes at the high frequency end may be caused due to a thinner layer.

4.3 Off Cochin—Arabian Sea

The water depth is 30 m with a sediment bed of silt. The SSP is downward refracting with a gradient of about 8 m/s. At the surface layer, sound speed does not vary much;

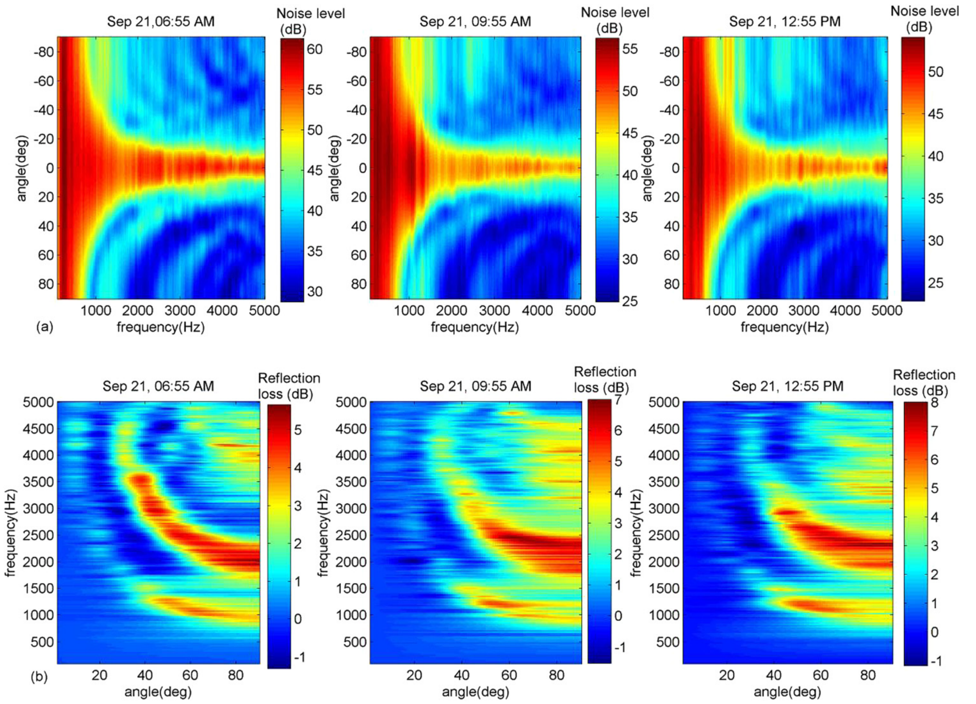

Fig. 2. (Color online) (a) Vertical directionality and (b) RL estimated from array measurements off Cuddalore for three data sets recorded within 6 h during forenoon.

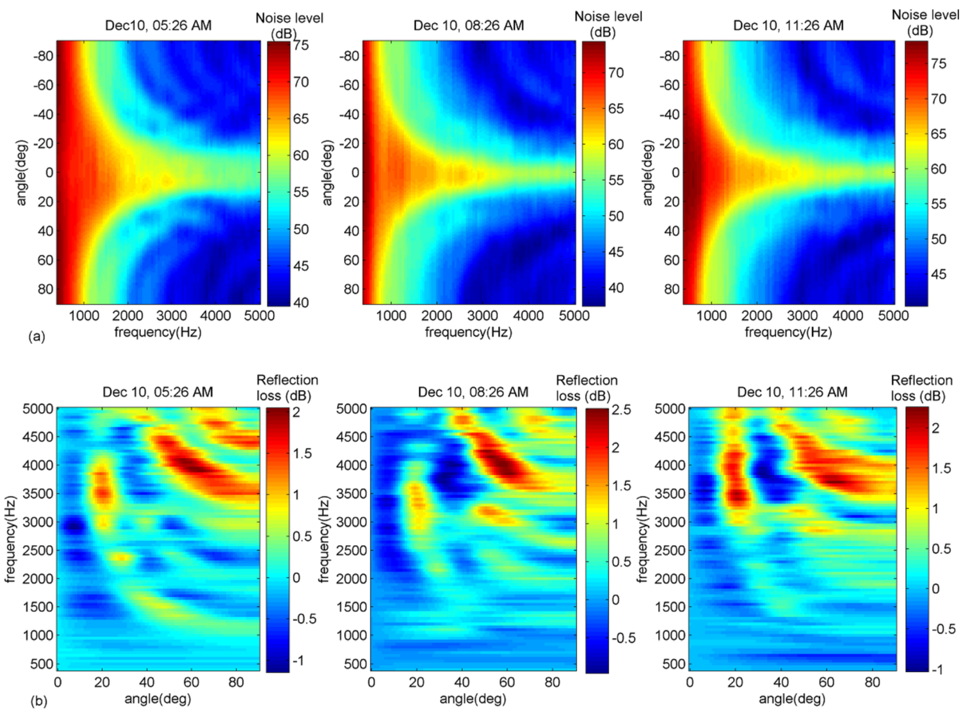

Fig. 3. (Color online) (a) Vertical directionality and (b) RL estimated from array measurements off Visakhapatnam for three data sets recorded within 6 h during forenoon.

beyond that, a strong gradient is seen. The critical angle at the site is estimated to be $\theta_c = \arccos(1538/1615) = 17.76°$. The continental shelf gradient is 0.15°.

Downward refraction at the site leads to bottom duct and surface bottom reflections. The summer profile gives rise to a NN in the horizontal. Since the sea bottom is soft, the bottom energy is less intense. Theoretically, a NN of 5.42° has to be present as given in Sec. 2, which is evident in the directionality pattern also but due to the proximity of the shipping channel, the notch region is getting filled [Fig. 4(a)]. In the RL plot [Fig. 4(b)], the low frequency end does not show any prominent fringes. The coarse fringes at the high frequency end may be due to thinner layers beneath. The loss maximum is seen around 50° to 60°, beyond 2 kHz.

When compared to other shallow water results for RL,[2,7,15] the loss is found to be comparatively low here. There may be many possible explanations. The wind speed during the period of measurement for all the three sites falls within 2–3 beaufort. When the surface noise is weak, dominant horizontal components lead to a similar response in the upward and downward direction. Hence, the reflection coefficient tends to unity, and the loss is also less in this case (0–8 dB). Also, an extremely shallow environment ensures that the difference in up/down flux is less. Among the three sites, Visakhapatnam has the low sound speed water column with an upward refracting SSP. The propagation is mainly through the SD, and not influenced by bottom reflection. This may be the reason for minimum loss at this site.

The critical angle (from *in situ* sound speed) is highest for the sandy site with 28.12°, followed by the silty site with an angle of 17.76°, and the clayey silt site with 12.12°. The critical angle from AN properties also correlates well with values of 25°, 20°, and 15° for Cuddalore, Cochin, and Visakhapatnam, respectively. The three sites represent different acoustic environments in terms of SSP and bottom properties, which are also reflected in noise measurements.

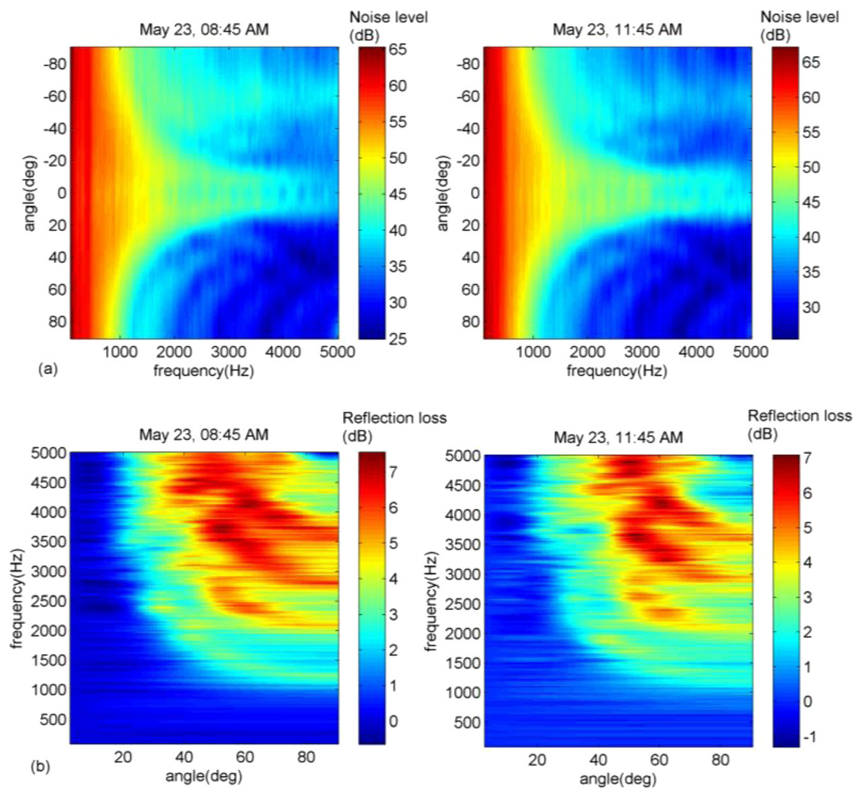

Fig. 4. (Color online) (a) Vertical directionality and (b) RL estimated from array measurements off Cochin for two data sets recorded within 3 h during forenoon.

5. Conclusions

The theoretical approach developed by Harrison and Simons[2] is applied to AN noise data from extremely shallow sites to acquire seabed information. This is supported by SSP, wind speed, and sediment data in inferring sound propagation. Noise directionality and RL derived from vertical array measurements clearly exhibit site specific characteristics. Directionality is temporally varying, but reflection property is the same for a particular site. Hence, it is a probable candidate for geoacoustic inversion studies. Furthermore, for propagation modeling, especially ray based models, RL is a sufficient representation of the bottom; hence, it can be applied as a model input. The critical angle derived from noise measurements matches with the critical angle calculated theoretically from water column SSP and sediment samples. The results given here are representative of a warm tropical environment with high water column sound speed. This is the initial attempt made in the North Indian Ocean toward sea bed characterization using passive measurements of AN. Further matched field inversion using model and field data will be carried out for detailed geoacoustic characterization.

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