Directionality and coherence of underwater noise and their impact on sonar array performance

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ABSTRACT

Fundamentally, sonar detection depends on extraction of the target signal from underwater noise by spatial and temporal processing of the received inputs. Spatial processing involves coherently adding, with appropriate weighting and phasing, the inputs from distributed sensor array elements to extract the more directional (more correlated) signal from the less directional (less correlated) noise. Knowledge and understanding of the directionality and coherence characteristics of underwater noise is therefore important for the optimum design, operation, and performance assessment of sonar arrays. This paper reviews ambient noise directionality measurements in both deep and shallow waters, with particular emphasis on the medium frequencies where sea surface-generated noise dominates. We discuss the effects of the environmental propagation conditions on the level and directionality of the ambient noise. The noise directionality patterns are interpreted in terms of sound propagation characteristics influenced by sound speed profiles, surface ducts, surface and bottom reflections, internal waves, and range-dependent bathymetries. We also illustrate the effect of noise directionality on spatial processing gain by considering the response of simple sonar arrays.

Keywords: Ambient Noise, Directionality, Coherence, Noise Notch, Deep Water, Shallow Water, Sonar.

1. INTRODUCTION

The ambient noise environment is a major factor affecting sonar performance. Ambient noise can be divided into two major components—the diffuse ambient background and discrete interferences. The diffuse component may originate from unresolvable distant shipping, wind -generated bubbles, rain, and biological choruses. The discrete component may be from strong shipping noise nearby, geophysical exploration, seismic events, and biological vocalisations. The diffuse component can mask the target whereas the discrete component can muddle and clutter intended sonar detections. In this paper, we are mainly concerned with the diffuse component.

Sound produced by the ambient noise sources propagates to a receiver through the complex underwater environment. Variation in sound speed due to temperature, salinity and pressure changes causes sound to refract upwards or downwards. Sound may interact with the surface and the sea bed by reflection and scattering. Hence seabed sediment type, roughness, rough sea surface and bubbles also affect propagation loss. The noise arriving at a distant point is a complex sum of many paths that may or may not interact with the seabed and sea surface.

Understanding and predicting the performance of active and passive sonars requires information on the levels, spectra, and directionality of the ambient noise in the areas of interest. Ambient noise modelling is often used in lieu of at-sea measurements due to cost and time constraints. Ambient noise models fall into two categories, complex mathematical models based on acoustic propagation and simple semi-empirical formulas based on some sparse measurements.

Empirical tables and curves can be used to estimate mean noise levels in generic environments (e.g., 1, 38, 43, 47) and in waters around Australian (14, 19, 20, 21, 39). However, these tables and curves do not provide information on the directionality and coherence of the noise field. Knowledge and understanding of the directionality and coherence characteristics of underwater noise is also important for the optimum design, operation, and performance assessment of sonar arrays.

For detailed understanding of the noise field including its directionality and coherence statistics at specific sites, more complex modelling is often used. In complex ambient noise models, noise sources are defined at particular locations as a function of level and frequency. These sources are then propagated to the point of interest using a model of propagation, which can be based on various approaches such as ray (31), normal modes (40), parabolic equation (17), energy flux (34,35), and simplified transport theory (41). Each model has strengths and weaknesses in terms of complexity to run, fidelity of results, time to run and frequency/environment applicability. Numerical noise models are reviewed in Etter (30).

This paper takes an empirical approach and reviews ambient noise directionality measurements in both deep and shallow waters, with particular emphasis on medium frequencies where sea surface-generated noise dominates. The focus is on understanding the effects of the acoustic propagating environments on the level and directionality of the ambient noise. The noise directionality patterns are interpreted in terms of sound propagation characteristics influenced by sound speed profiles, surface ducts, surface and bottom reflections, internal waves, and range-dependent bathymetries. We also illustrate the effect of noise directionality on spatial processing gain by considering the response of simple sonar arrays.

2. NOISE DIRECTIONALITY

For simplicity, sonar detection range prediction often assumes that ambient noise is isotropic. However, ambient noise can be highly directional, especially at medium frequencies (1 to 10 kHz) where wind-generated surface noise dominates.

The directionality of the oceanic noise depends on the source characteristics and the propagation factors. The sea surface is acoustically soft and reflections from the sea surface introduce virtual mirror image sources with phase reversal. Hence noise sources of monopole nature near the sea surface couple into the water column with dipole radiator characteristics. Frequency-dependent propagation of sound in the ocean determines the range at which noise sources are important. The influence of noise radiated at higher frequencies is more localized because of greater absorption in the seawater and higher boundary reflection losses, whereas noise radiated at lower frequencies travels further and is more affected by environmental propagation effects.

The level and directionality of ambient noise is important for sonar performance predictions in several aspects. For example, understanding of the spatial distribution and horizontal directionality helps to avoid operating a sonar where a target is in the same sector as high levels of ambient noise; ambient noise sometimes has a region of lower levels near horizontal that can be exploited to enhance detection by creating a window to look through the noise for targets of interest; and advanced beamformers based on noise cancellation algorithms depend on the distribution of the discrete components of the ambient noise field to improve the array gain.

2.1 Propagation Effects

The level and directionality of ambient noise can be interpreted and understood in terms of source radiation patterns and environmental propagation conditions. The directionality depends on receiver depth, acoustic frequency, the sound speed profile, bottom depth and seafloor reflectivity. One example is given in Clarke (24, Fig.11) for a location in the Norwegian Sea with a receiver at a depth of 198 m in water of moderate depth (1774 m), where the noise directionality patterns are interpreted in terms of sound propagation characteristics influenced by sound speed profiles, surface ducts, and bottom reflections. The noise level has a notch at angles around horizontal due to a low-angle shadow zone caused by a negative profile gradient, and is higher at upward-looking angles and lower at downward-looking angles due to bottom absorption.

3. DEEP WATER

3.1 Frequencies 50 - 500 Hz

A general feature of the vertical directionality of ambient noise in deep water is that lower frequency noise from distant shipping (2,32) or wind (6,14,22,23) arrives near horizontal and local wind-generated higher frequency noise had its peak intensities near vertical. Propagation analysis in range-independent environments predicts the existence of a noise notch near horizontal. However, the notch is not always observed at sea, especially at low frequencies, which presents a paradox. The paradox has been explained by the effects of range-dependent propagation. One effect is the conversion of near-surface noise at steep angles from ships transiting continental shelves and slopes into shallow-angle propagation paths by downslope propagation. Another effect is the ducting of near-surface wind noise from high latitudes, where the sound channel is near the surface, to deep sound channels in middle-and-low latitudes.

3.1.1 Noise Notch

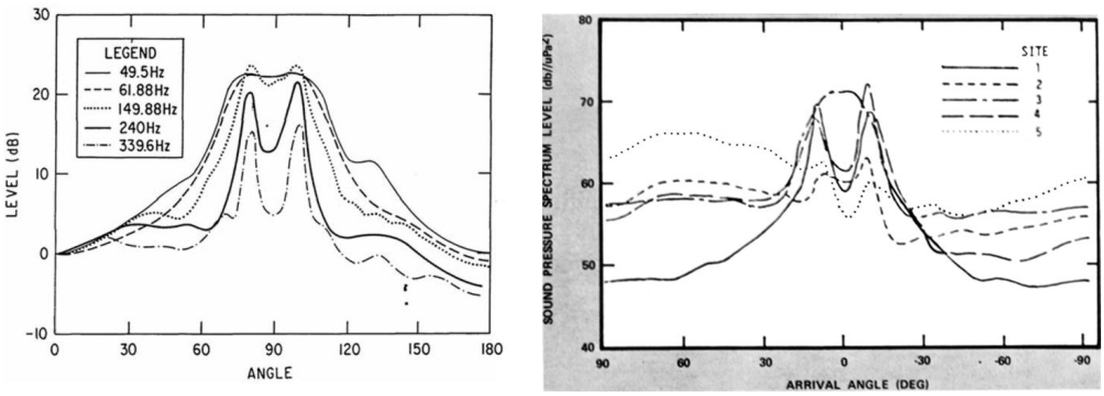
The noise notch is a well-known phenomenon in vertical noise directionality and results from a combination of downward refraction and the dipole structure associated with distant sources near the pressure release ocean surfaces. In range-independent (horizontally homogeneous) deep-ocean environments with a deep-sound channel, propagation analysis indicates that noise energy due to surface sources will be concentrated in the positive and negative elevation angles corresponding to those ray bundles which intersect the surface. There will be an angular noise notch near horizontal defined by the limiting rays leaving the source horizontally. Noise generated from surface sources cannot arrive within the limiting angles. Based on Snell's law, it is easy to see that the angular width of the noise notch is given by the arccosine of the ratio of the sound speed at the receiver and the surface source.

Range-dependent effects, such as slope conversion, horizontal sound speed variation, may convert energy at steeper angles to shallow-angle propagation paths and fill (or partially fill) the notch, particularly at low frequencies when long range propagation effects are important (2). At these lower frequencies, the deep water noise notch can be filled by noise from distant shipping and high-latitude winds when down-slope propagation and shoaling of the sound channel convert noise from steeper rays to more horizontal paths (6, 17).

3.1.2 Downslope Conversion

Bottom reflectivity is higher at low frequencies. Hence the bottom acts as a low-frequency pass filter. Owing to the angle of the slope, the downward-directed energy reflects with a reduction in grazing angle of twice the slope angle. This reduction of the angle of propagation couples the sound from surface-ship- and wind-driven noise at lower frequencies over the slope into the sound channel. The low frequency energy at higher angles interacts with the bottom and is converted to low-angle energy in the deep sound channel, while at the higher frequencies energy is absorbed. Therefore we see that the noise notch near horizontal is filled at lower, but not higher frequencies.

Figure 1(a) shows measured vertical noise directionality (16,18) in the Sargasso Sea south of Bermuda. These data were obtained with a vertical array of 26 elements spanning a distance of 110m centered at a depth of 236 m in the deep sound channel with an axis depth of 1 km. At the higher frequencies, the pattern is peaked at angles given by the arccosine of the ratio of the sound speed at the receiver and the surface (about ± 9.5^{o}) with a notch at the horizontal. At the lower frequencies, the notch is filled by low-angle energy from downslope conversions from continental slopes and sea mounts, and the pattern shows a broad pedestal centered on the horizontal direction.



(a) (b)

Figure 1 – Vertical directionality of ambient noise (0^{o} is up)

(a) at specific frequencies at a site south of Bermuda (reproduced from ref. 18).

(b) at 380 Hz for five sites in the western north Atlantic (reproduced from ref.33).

Figure 1(b) shows a combination of shipping noise near the horizontal and surface generated noise at 380 Hz for five sites in the western north Atlantic (33). Sites 1, 2, 4 and 5 show peaks at approximately ±8° angles, which correspond angles given by the arccosine of the ratio of the sound speed at the 1,000-foot array center depth and the surface. The data from site 3 did not show this characteristic shape due to corruption by seismic profiling equipment approximately 400 nm away.

3.1.3 Persistent High-Latitude Winds

Bannister (6) discussed the ambient noise from the persistent winds which blow over the oceans at high latitudes ("the roaring forties") where the sound channel axis reaches the surface. Noise energy is ducted into low-loss paths in the deep sound channel by favorable horizontal sound-speed gradients and reaches long distances at low frequencies. Due to strong westerlies at high southern latitudes, the high-latitude, wind-noise contribution is greatest in the Southern Hemisphere and is comparable to that from light-to-moderate shipping. The noise arrives within 15 degrees of horizontal and provides another mechanism to fill the noise notch besides downslope conversion.

3.2 Frequencies Between 0.5-10 kHz

Figure 2 shows the transition of the vertical directionality of ambient noise from 200 to 1500 Hz in sea state 3 measured near the bottom in 4420 m deep water off Bermuda (Figure 5-4, 46), showing more shipping noise coming from the horizontal at the lower frequencies and more wind-noise from vertical at higher frequencies.

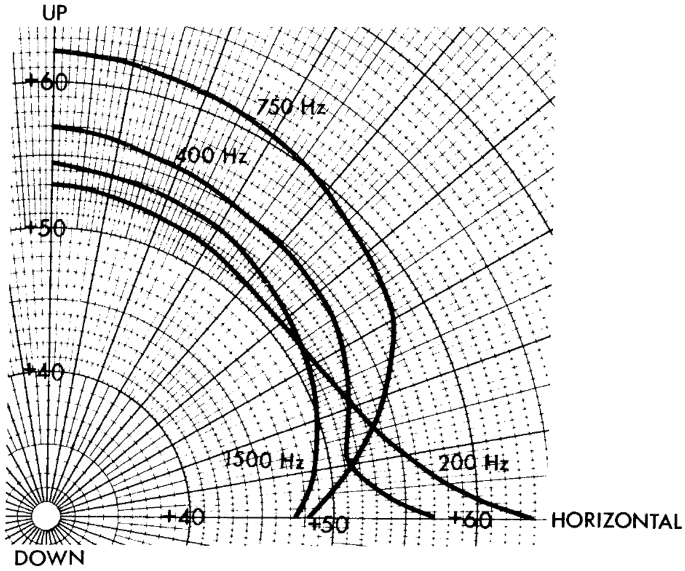


Figure 2 – Vertical directional patterns averaged in 1/3-octave bands at four frequencies in sea state 3. The scale is spectrum level in dB re 1 µPa per Steradian (reproduced from ref. 46).

The vertical coherence of the noise field was measured from the sea surface to a depth of 6000 m in the northern Philippine Sea by a gravity-buoyancy driven instrument that descended and ascended the water column (12). Data analysis shows that between 1 and 10 kHz the variation of the noise with frequency is consistent with the wind noise spectra of Wenz (51,52). The vertical coherence of the noise closely follows the simple expressions given by Cron and Sherman (26) for surface-generated ambient noise in an isovelocity, infinitely deep ocean, provided the local sound speed is used in evaluating the theoretical expressions, implying a depth-independent directionality with a simple cosine law. The spatial coherence of the noise show no change in character in the vicinity of the critical depth, indicating the noise originating in local, wind-driven surface sources rather than distant shipping. The absence of a detectable upward propagating component indicates that reflections from the fine-grained, soft sediment are negligible.

4. SHALLOW WATER

4.1 Sound Speed Profiles and the Noise Notch

Shallow water noise is more spatially and temporally variable, and the vertical directionality is strongly affected by the sound-speed profiles and bottom reflectivity. Qualitatively, ray analysis helps to understand the vertical directionality of the noise field for different types of sound speed profiles. For a downward refracting profile, rays emanating from sources on the surface tend toward the bottom and at the point or receipt, there are no rays propagating horizontally, leading to the noise notch (an equivalent modal interpretation of the noise notch is that near-surface sources excite preferentially high order modes with steeper propagation angles). For an upward-refracting profile (i.e., surface ducts), rays emanating from sources tend toward the surface and so horizontally directed rays reach the receiver. These propagation characteristics, in combination with the source radiation pattern, affect the vertical directionality of the noise. Detailed modelling (53) shows that the noise notch occurs at constant or downward refractive profiles.

4.2 Low Frequencies (50 – 1000 Hz)

Measurements of ambient noise between 50 and 800 Hz at a site in the South China Sea show that the ambient noise field varies significantly with time and frequency. Distant shipping noise was observed near the horizontal angles, and surface noise occurred at high grazing angles. Noise at 100 Hz was not affected by wind speed and was mainly from distant shipping. The noise notches, with peaks at about 10 to 15 degrees from horizontal, often appeared at 200 and 400 Hz at daybreak when the sound speed profile was downward refractive (49,50). It was also observed that the character of the noise field varied with the variability of the propagation conditions induced by internal tides.

4.3 Mid-Frequencies (1 - 10 kHz)

Clark (24) reviewed the vertical directionality of wind-generated noise in downward refracting environments in two measured data sets. The first data set was obtained with a vertical line array moored near the bottom in 200 m of water in the Gulf of Mexico (GOM) and the width of the noise notch is about ±10 degrees at 2473 Hz. The second data set was obtained at a receiver depth of 200 m in water depth of 700 m off a slope in the Tongue of the Ocean (TOTO) in the Bahamas. Both data sets are from receivers in the thermocline below surface ducts. Both data sets show higher noise levels at upward-looking angles and lower levels at downward-looking angles, and noise notches near-horizontal angles. These three regions correspond, respectively, to noise arriving at the receiver on direct paths from the surface, noise reflected to the receiver from the ocean bottom, and low-angle notches due to ray shadow zones. Modelling by Clarke (24) using an integrated mode formulation with an effective dipole source model matches well the directionality and noise notch in both data sets.

Here we understand the width of the noise notches based on a simple interpretation using Snell's law. The sound speed profiles corresponding to both data sets consist of surface ducts with the receivers below the ducts in the thermocline. The notch width should approximate the received angle of the limiting ray leaving the bottom of the surface duct at horizontal. For the GOM data set, Fig.3 of Clarke (24) shows that the sound speed at the bottom of the surface duct is about 1542 m/s whereas the sound speed at the receiver below the duct is about 1510 m/s. Hence the received arrival angles of the rays leaving the duct at horizontal angle are given by arccosine(1510/1542) = 12 degrees. Similarly, for TOTO data set, Fig.9 of Clarke (24) shows that the sound speed at the bottom of the surface duct is about 1537 m/s whereas the sound speed at the receiver below the duct is about 1531 m/s. Hence the received arrival angles of the rays leaving the duct at horizontal angle are given by arccosine (1531/1537) = 5 degrees. These simple estimates of the notch width matches the data well.

4.4 Notch Filling

The noise notch can be "filled in" by scattering effects from the ocean surface, bottom, and volume inhomogeneities, in particular shallow water internal waves. Furthermore, the scattering also redistributes steeper angle noise energy into low grazing angles that can propagate to long distances. Hence the filling-in of the notch, although occurred locally at the sites of the internal waves, can extend well beyond the area of the internal waves.

4.4.1 Internal Waves

Range-dependent effects such as internal waves cause energy transfer between different modes. Low order modes are strengthened and higher order modes are weakened, the notch becomes shallower. Analysis and modelling of ambient noise data from the East China Sea in the 1-to-5-kHz band show that range-dependent effects in the environment such as internal waves may redistribute the noise into shallower angles and partially fill the notch. For example, the noise notch depth varied from over 10 dB when internal waves are neglected to about 5 dB for internal waves of moderate strength (42).

4.4.2 Volume Scattering at High Frequencies

Aredov (3) hypothesizes that volume scattering may provide an isotropic floor to the noise notch. However, there is no known experiment that has confirmed this notch-filling mechanism. A ray-based model has been developed to explore the sensitivities of surface source directionality, volume scattering, element directionality and discrete shipping noise to the mid to high-frequency performance of a vertical line array and a volumetric array (31), in particular, it has been found that nearby shipping may fill up the notch.

5. SPATIAL COHERENCE

Noise coherence and directionality are inter-related. For noise fields that consist of a summation of statistically independent plane waves with random orientation, the spatial coherence of the noise field between a pair of sensors in an arbitrary orientation is related to the directionality of the noise field via mathematical transform-type integrals. In particular, the coherence in vertical or horizontal direction is related to the noise directionality via Fourier or Hankel type transform (25,26). Such a plane-wave noise field is also spatially homogeneous and its coherence function depends only on the separation and orientation of the sensors, but not their absolute positions.

It is easier to measure vertical coherence using a pair of sensors than to measure directionality using a sensor array. So investigation of ambient noise vertical directionality is sometimes performed by measurement of the vertical coherence.

Table 1 summarizes some of the work on spatial coherence of the different types of noise fields with various descriptions of directionality.

Table 1 – Coherence of noise fields with various directionality

Noise Field Types	References
Iso3D: 3D isotropic	Burdic (13, Sec. 10.2.2)
Iso2D: 2D isotropic noise, elements in propagation plane	Burdic (13, Sec. 10.2.5)
CS: surface dipole sources, isovelocity water, no bottom reflections: horizontal & vertical coherence	Burdic (13, Sec.10.2.4, Sec. 10.2.6) Cron & Sherman (26)
Sum of surface noise, bottom reflected noise, 3D isotropic, 2D isotropic noise	Burdic (13,Sec.10.2.7)
Gaussian functions defined in terms of offset and width	Stockhausen (45)
Cox-L: deep (4400 m) water off Bermuda, sensor near bottom, low frequency (112 Hz)	Cox (25), Axelrod et al (5)
Cox-H: deep (4400 m) water off Bermuda, sensor near bottom, high frequency (1122 Hz)	Cox (25), Axelrod et al (5)
Cox-M: deep (4400 m) water off Bermuda, sensor near bottom, intermediate frequency (400-800 Hz)	Cron, Hassell, Keltonic (27) Cox (25)
BB: deep (6000 m)water, Philippine Sea, all sensor depths, wind noise (1-10 kHz)	Barclay Buckingham (12)
DBT-1: Vertical coherence: shallow water (mud bottom) off Eureka, California, wind noise (< 20 kHz)	Deane, Buckingham, Tindle (28)
DBT-2: Vertical coherence: shallow water (fine sand) Jellicoe Channel, New Zealand, wind noise (< 20 kHz)	Deane, Buckingham, Tindle (28)
CDB-1: Vertical coherence: shallow water (rock bottom) off Cortes Bank, California (250 – 2500 Hz)	Carbone et al (15)
CDB-2: Vertical coherence: shallow water (thin layer of sand over chalk) North Celtic Sea, (100-1000 Hz)	Carbone et al (15)

Case Iso3D is 3D isotropic noise where the noise power is the same per unit steradian in all directions. This is often the approximation used in sonar performance modelling for simplicity or due to the lack of detailed information. It may be a good approximation at some frequencies between a few hundred Hz to 1 kHz when the noise consists of well-balanced wind-generated noise and distant shipping noise.

Case Iso2D is 2D isotropic noise where the noise power is uniformly distributed in a particular azimuthal direction. This approximation may be used when the noise field is azimuthally homogeneous, but with sharp peaks along particular elevation angles (54).

Cases CS is a theoretical model developed for surface-dipole generated noise fields over an infinitely deep ocean with a uniform sound speed profile (26). It is a good approximation for mid-frequency wind noise in a deep ocean with weak bottom reflections (12). The vertical and horizontal coherence are suited for assessing the performance of horizontal or vertical arrays in such fields.

Cases Cox-L, Cox-H, Cox-M are suited for noise fields that consist of vertical (often wind or rain generated) and horizontal (often shipping) components of different weighting at different frequencies.

In Cases DBT1-2 & CDB1-2, it was shown that the time-averaged coherence of the noise field are more temporally stable than the noise intensity. The vertical coherence from a single hydrophone pair in shallow water was used to estimate the seafloor acoustic properties for fluid-like and shear wave-supporting seabeds.

6. Modelling Array Performance

The performance of a sensor array to suppress noise can be computed from either integrals involving noise directionality and the array beam pattern, or summations involving noise coherence across the array elements.

6.1 Wind-Noise over Deep Ocean

Figure 3 illustrates the effect of noise directionality on array gain (conventional beamforming, no shading) of a uniform line array of 9 equally-spaced elements with element interval of 0.15 m (cut frequency = 5000 Hz). The signal fields are assumed to be fully coherent plane waves across the array's apertures. The beam is steered in the direction of the signal and there is no mismatch loss.

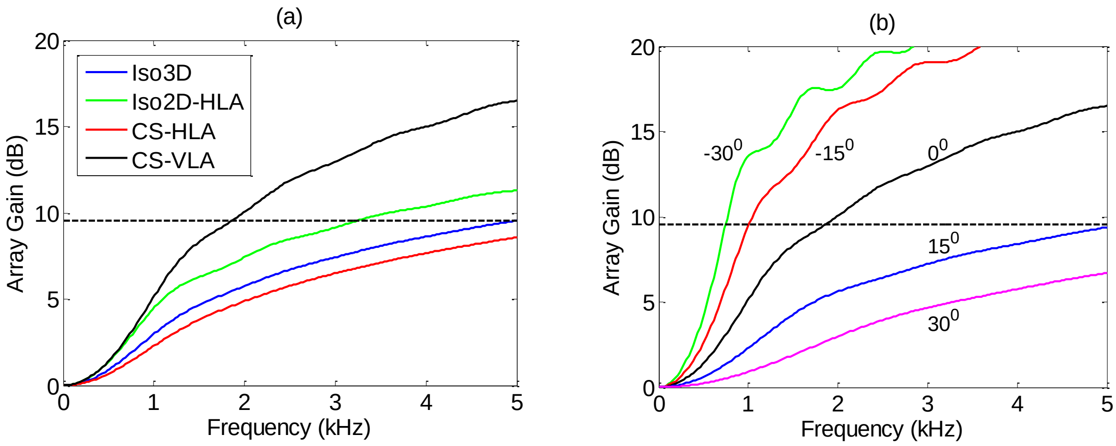


Figure 3 – Array Gain (a) in noise fields of different directionalities, steered broadside; (b) vertical line array steered at various elevation angles in surface dipole noise field.

Figure 3(a) shows the array gain when the array is steered broadside in the first 3 types of noise field directionalities in Table 1, i.e., 3D isotropic noise, horizontal line array (HLA) in 2D horizontal isotropic noise, HLA and vertical line array (VLA) in surface dipole field. The dashed line is for spatially white noise, i.e., the noise is uncorrelated for any separation of a pair of sensors. The array gain is independent of frequency and steering directions and equals the number of elements. Uncorrelated noise can be a good approximation for noise such as array flow noise or electrical noise.

We note that in the surface dipole noise field which is strongly downward propagating, the VLA being steered horizontally achieved a much greater gain than the HLA being steered broadside.

Figure 3(b) compares the array gain when the VLA in surface dipole noise field is steered at different elevations. The two black lines in Fig.3(a)&(b) are the same and are the gain when the VLA is steered horizontally. Because the noise field propagates strongly downward, the VLA has greater gain when steered downward (negative angles) and less gain when steered upward.

6.2 Rain Noise in a Shallow Water Waveguide

Figure 4 shows the modeled noise directionality generated by light rain (precipitation rate of 1 mm /hour) in an isovelocity shallow water waveguide (54). Rain noise is generated by direct forcing as rain strikes the water surface and by wake cavity formation and bubble pulse oscillation as the rain drives down into the water. The noise source strength is estimated by Eqs.(60-63) of APL-TR9407 (1). The modelling followed the approach of Desharnais and Chapman (29).

The directionality is a composite effect of dipole radiation pattern from the surface, which favors noise energy at steep angles, and seafloor reflectivity, which favors energy at shallow grazing angles. The resulting directionality has twin peaks at about ± 21 degrees, less than the critical angle of seabed reflection (28 degrees). We also note that because energy reflection loss from the sea surface is much less than that from the sea bottom, noise is stronger in the downward looking (positive grazing angles) than in the upward looking (negative grazing angles) directions.

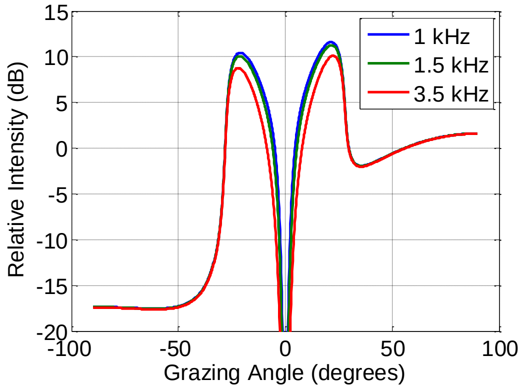


Figure 4 – Directionality of the rain noise in a shallow water waveguide

7. Exploitation of Ambient Noise Directionality and Coherence

In shallow water, the vertical directionality and correlations of the noise field are strongly affected by interactions with the sea floor. In particular, due to bottom absorption, the noise is typically stronger looking above horizontal than looking below horizontal (3, 7). The ratio of the downward-looking and upward-looking noise intensities can be used to estimate bottom reflectivity (4, 36). Other properties of the sea floor that can be inferred from the characteristics of the noise fields include critical angles (8), compressional and shear wave speeds (15), and sub-bottom profiles (37,44).

Using ambient noise to infer seafloor properties has the attractive feature of being covert, low power, and marine mammal friendly. However, better angular resolution requires a longer vertical array, which has disadvantages in cost, ease of deployment, and array deformation. A synthetic-array processing technique has been developed to improve the angular resolution of short vertical arrays (44).

8. CONCLUDING REMARKS

This paper reviewed the vertical directionality of ambient noise measurements in both deep and shallow waters and discussed the effects of environmental propagation conditions on the directionality of the ambient noise. The noise directionality patterns are related to sound propagation characteristics influenced by sound speed profiles, surface ducts, surface and bottom reflections, internal waves, and range-dependent bathymetries. We also illustrated the effect of noise directionality on spatial processing gain by considering the response of simple sonar arrays.

Due to length limitations, our discussions have excluded horizontal directionality of the ambient noise, which is generally associated with various acoustic sources including surface shipping, localized storm systems, and underwater seismic events. We also had not discussed directionality of biological noise, such as marine mammal sounds, fish choruses, and snapping shrimp noise. Biological noise forms a major component of the ambient noise in many shallow tropical waters around Australia, but it is highly variable in space and time. Little data exist on the directionality of biological noises. In theory, noise models may be used to compute the directionalities of biological noises if the spatial and temporal distribution of the sources can be estimated or measured. Given the importance of biological noise in Australia waters, more work needs to be done in these areas.

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