Chapter 6
Research Issues and Applications of Oceanic Noise

Summary

Ambient noise calculations have traditionally been of naval interest as necessary sonar performance prediction tools. Performance prediction systems had as their primary purpose the allocation of resources and the estimation of system performance in the development of tactics. Since these prediction system could be site-specific, experimental results obtained by sonar systems could be utilized to provide refinement of the environmental acoustic parameters. Recently ambient noise calculations have had an additional role in the conduct of environmental-acoustic impact assessments.

Maritime nations have a responsibility for the safe, clean utilization of the invaluable ocean resource. Recreational, industrial, fishery, aquaculture, and military uses of the ocean resource require quantitative knowledge of the oceanic noise field and the influence these activities have on the environment and the biological systems. In planning for the future economic utilization of this resource, environmental-acoustic impact assessments will require the estimation of noise levels. The quantitative understanding of the physical, biological, and machine-source mechanisms of radiated sound necessitates the development of acoustic noise models based on physical principles that span multiple disciplines.

Knowledge of natural physical production of sound in the ocean has rapidly increased in the last several decades. Theoretical descriptions of transient radiation from microbubbles, microbubble clouds, spray, splash, rain, and turbulence were discussed in Chapters 3 and 4. These physical mechanisms and mathematical methods presented can be adapted for the purpose of ambient noise calculations; but the numerical representation of these sources as well as the description of the sonic radiation from the air–sea boundary interaction zone are still work in progress. In addition, research is required to develop models of radiated noise from man-made machines.

The propagation of sound from the sources of sound in both deep and shallow waters is a key research issue because it is strongly influenced by the variable oceanography. For example, in most shallow water coastal environments, seasonal cooling and warming along with river outflow, tides, and currents produce a variable sound speed structure in depth, range, and time. Wave-theoretic range-dependent

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propagation codes such as the wide-angle parabolic equation and Gaussian-beam ray codes have been shown to accurately calculate the sound transmission provided appropriate environmental input parameters are used. Past determination of these parameters used large, cumbersome and inefficient archival databases. Satellite observations, archival information coupled with acoustic, basin bathymetry, oceanographic models could provide a method to determine the spatial and temporal variability of the range-dependent oceanographic characteristics of the waveguide. This type of assimilation could provide the basis for synoptic calculations and development of spatial sampling and sensitivity criteria. Furthermore, parallel, "cloud-like," processing should provide for rapidity. In addition, this type of technology can be adapted to utilize the noise field measured on a horizontal, vertical, or volumetric array to perform an estimation of the modal structure and bottom properties using a variety of inversion algorithms [see Buckingham (1987), Siderius et al. (2006), and Harrison et al. (2009)].

At the higher frequencies (above 1 kHz), the Fast Ambient Noise Model and Ambient Noise Directionality Estimation System used geometric acoustics to calculate the vertical directivity of noise. A variety of time-ranged averaged noise codes used convolution to rapidly estimate omnidirectional levels and the directional response of sonar systems. The computational speed of these earlier codes was retained by use of a hybrid ray-mode propagation code, the adiabatic approximation, and range-averaged propagation loss in the Ambient Noise Directionality Estimation System. A recently published application by Wagstaff (2005) to the Northeast Pacific Basin provides a significant example of the validity of the approach and the ability to compute the persistent directional field characteristics of a large basin.

At lower frequencies, the parabolic approximation to the acoustic wave equation due to Tappert (1977) and further developed by Collins (1992, 1993) provided an alternative to adiabatic normal modes. The method incorporates vertical mode coupling needed to accurately describe downslope conversion and the associated contribution to the vertical directivity. The importance of this downslope effect was shown computationally using the parabolic approximation. Jensen (1994) provided a complete description of the computational results with a parabolic equation code to demonstrate the downslope conversion process, and a summary of experimental results may be found in Carey and Wagstaff (1986).

A new computationally extensive calculation of the noise field for the Northeast Pacific Basin was presented in Chapter 5. This wave-theoretic estimation preserved the amplitude as well as the phase of the acoustic noise field and determined the spatial coherence characteristic and array response. In Chapter 5, the assimilation of satellite wind speed, measured source level, and a physical acoustic source model were combined to produce the wind-driven source level per square meter of surface area shown in Fig. 5.13. This source level per square meter of surface area can be updated with a wind speed to produce a temporal calculation of the noise field. The assimilation, computational speed, and treatment of spatially distributed sources is unique. The azimuthal array response was obtained on a sector-by-sector basis shown in Fig. 5.15. Fall sound speed profiles were calculated with a oceanographic model, bathymetry was from a digital bathymetric database, and bottoms of a silty clay for the basin (0° critical angle) and a sandy silt (20° critical angle) for the slopes were used. These choices of environmental variables are the major source of uncertainty in this computation and the reflectivity of the slopes in particular is largely unknown and important.

The low-frequency (50-Hz) vertical directionality as a function of bearing and depth for the basin shipping noise is shown in Fig. 5.18. The major uncertainty in this calculation is the distribution of ships and the source level of ships as a broad representative class. In recent years the size and variety of commercial ships has increased dramatically. The propulsion of commercial ships has evolved from single propellers to dual propellers and multiple types of drives. This situation is further complicated owing to the diversity and size of offshore work boats, fishing boats, and passenger boats. The problem one has with the radiated noise levels from surface crafts is the paucity of calibrated measurements and analytical treatments of the frequency-dependent noise mechanisms. Certainly, one would expect an increase in both deepwater and shallow water noise due to man′s activities; the question is the rate at which this increase is occurring. Is the proposal of Ross (1976, 2005) accurate or does this need to be modified to include changes in the radiation level and efficiency with the type of vessel?

The combined application of theoretical acoustics, computational acoustics, applied ocean physics and assimilated satellite observations to the rapid computation of the ocean noise field was shown to be the feasible; however the potential utility to provide environment assessments still needs to be demonstrated. The essence of an accurate noise calculation is a physical understanding of noise production mechanisms, the complex range dependent oceanographic environment, the range and azimuth variation of the bathymetry along with its geophysical composition, the importance of the air-sea boundary interaction zone and the dynamic shipping radiation characteristics. In summary the research question is: if given an accurate numerical source representation, an assimilated satellite sea surface observations, bathymetry, oceanographic model and a method to calculate sound transmission, how accurately can the coherent noise field be estimated?

Noise Mechanisms

The previous quantification of the natural physical mechanisms responsible for noise production near the sea surface required the transient treatment of the radiation from microbubbles, microbubble clouds, and impact noise from rain, spray, and splash. Theoretical expressions for the natural physical sources of sound provide a basis for developing numerical representations. However, the subsurface turbulent boundary layer and the presence of microbubbles convected to depth by the turbulence structure requires additional consideration owing to differences associated with the thermal stability of the boundary layers above and below the sea surface. Satellite sea surface temperature, wind speed, and whitecaps should provide a basis for determining the stability and thus by inference the requisite parameters to refine the frequency- and wind-speed-dependent source representations.

The characteristics of the complex air–sea boundary interaction zone presented in earlier chapters depended on the Reynolds number (R_e), the Richardson number (R_i), and the effective roughness determined by the integral of the sea surface spectrum. The computations, Chapter 5, used the source models coupled with estimates of the 10-m wind speed derived from specialized microwave radar that used pulses (13.4 GHz) and two spot beams in a circular rotation sensitive to scattering from the air–sea boundary. This system is NASA's Quick Scatterometer (QuikSCAT) and is widely used in determination of high-resolution global wind speeds required for estimates of atmospheric forcing and air–sea interaction climate studies. The technical issue for deep sea and shallow water noise computations is whether this wind speed estimate is sufficient or does one also need to use sea surface temperature and whitecap observations?

Finally, storm noise is an interesting and largely unexplored area of ambient noise research. In particular, lightening has been shown to produce interesting oceanic sound. In storms, very low frequency sound production due to wave interactions and large plunging breakers is another phenomenon to be investigated. Perhaps the reason for the lack of experimental and theoretical results is the difficulty of performing reasonable measurements. Snyder (2008) observed the noise field with omnidirectional hydrophones in the Gulf of Mexico for a period of 14 months, including four hurricanes. His measurements at higher frequencies were dramatically affected by the storms, whereas the lower-frequency noise actually decreased, most likely owing to the dramatic decrease in shipping. With satellite measurement such as shown Fig. 5.13 and a directional array (Fig. 5.15) or a submerged autonomous vehicle towed array, additional storm noise measurements could be possible.

Hydromechanical Sources of Sound

A major research issue is the radiation from ships, fishing vessels, oil platforms, and wind farms. The quantification of sound radiated from the modern ship should be parameterized by tonnage, draft, length, beam, type, and speed. A ship's sound radiation is known to be proportional to the power, number of propellers, number of blades, and rotation of the shaft [Arveson and Vendittis (2000), Gray and Greeley (1980)]. Since the hull and wake shadow the fore and aft directions, and the noise is primarily generated by propeller cavitation, the result is a dipole radiation pattern. The issue is whether a class of ships may be represented by an analytical model with horizontal and vertical directivity. Analytical models could also be developed for oil platforms and wind farms.

The determination of the appropriate source representations for surface ships, oil platforms, and wind farms should start with the use of measurements to develop realistic but simplified representations. An autonomous vehicle towed array system is capable of performing this type of measurement cost effectively because of its ability to vary parameters such as range bearing and depth. Such a towed-array vehicle system was developed to demonstrate and quantify the performance characteristics of adaptive signal processing algorithms, including dynamics [Carey and Holmes (2009), Holmes and Carey (2006)]. This technology provides for an effective tool for the measurement of coherent signal propagation and the directional noise fields. The stability of the system enabled the towing of an array some 40 m long capable of formation of synthetic aperture estimates of the modal horizontal wavenumber spectrum. Model-based extended Kalman filter techniques were found to enable both narrow band and broadband tracking [Sullivan and Carey (2009)]. This type of system can provide a unique measurement capability for the measurement of shipping noise source levels, downslope reflectivity, and shallow water geoacoustic inversions. In the case of shipping source levels, such a vehicle could proceed at depth while the ship proceeds on a steady course and constant bearing such as in current common practice. The precision vehicle navigation can then be used to construct the acoustic source characteristics from the measured field. Likewise, the radiation from any platform, wind turbine piling, or any other fixed industrial activity may be measured. Nichols (2005) illustrated some characteristics from oil exploration machines; however, this information is out of date and simply of historical interest. In general, there appears to be a paucity of this type of information available.

The theoretical treatment of radiated sound from ships has been reviewed by Arveson and Vendittis (2000) based on the work of Gray and Greeley (1980) and Ross (1974, see Ross (2005), 1976). These studies were for smaller vessels of approximately 25,000 dwt, 11,000 hp, and with single propellers of radial dimension less than 5 m. The average current (2005–2010) commercial ship is approximately 55,000 dwt with single propellers between 5 and 9 m in diameter. Since compact radiators can be represented by a multipole expansion and since the near field resulting from the vibrating propeller surface is intractable, can the determination of the radiating component by far-field measurements provide for the development of an elegant but simplified source model? This was the approach used to develop an analytical model of sound radiation from the bubble volume oscillation as the propeller rotates from high to low pressure. Several classes of noise sources such as ships were discussed by Ross (1976, 2005) and simplified analytical models were adequate to describe the far-field radiation; however, it is not obvious that more complex ships and oil exploration devices can be easily characterized. Can the measurement of the radiated far field provide for the development of an elegant but simplified source model? If the radiated sound from ships, platforms, and wind farms can be described by simplified analytical descriptions, then the calculation of the noise field is possible.

Geoacoustic Uncertainty

A major uncertainty in the computation of basin-scale deep water and coastal-scale shallow water is the range-dependent geophysical and derived geoacoustic characteristics. In deep water the primary uncertainty is the reflectivity of the continental slopes and sea mounts. Previous discussion (Chapter 4) has focused on the effects of the slope frequency-dependent reflectivity on the directional characteristics of the noise field. The conversion of high angles to lower angles for sources over the slope coupled with the frequency-dependent reflectivity was found to favor lower frequencies with slope enhancement, the megaphone effect. Although this effect has been well recognized (Carey and Wagstaff 1986), the actual reflectivities of the slopes are either unknown or not publicly available. Measurements of slope-reflected ambient noise or noise from an individual ship with deep-ocean-moored high-resolution arrays such as a Mills cross array (Urick 1983) or the end fire array of an autonomous vehicle could provide a basis for a model-based inversion to characterize the slope reflectivity. Basin-scale calculations for the Philippine Sea (Evans and Carey 2009) illustrate the uncertainty of this unknown by varying critical angles between 10° and 20° for frequencies of 50 and 200 Hz. The effect on the vertical and horizontal directionality was found to be considerable.

The continental shelves and deep but bottom-limited gulfs and seas also require knowledge of the geophysical and derived geoacoustic properties of the bottom. The bathymetry and general bottom composition to depths below the sediment water interface are known to a reasonable degree and can be obtained from digital archives. The fine-scale and roughness parameters are simply unknown and consequently the frequency-dependent reflectivity is very uncertain. Naval applications rely not only on geoacoustic profiles but also on site-specific empirical factors derived from measurements. This type of approach is not cost-effective on the scale required for noise computations. Claerbout (1968) proposed the use of low-frequency surface-generated noise for geophysical applications, whereas Buckingham and Jones (1987) showed under certain environmental conditions the bottom critical angle could be determined. The shallow water environment is usually characterized by winter isospeed or upward refracting profiles, spring profiles with variable surface sound speeds, summer profiles with downward refractions, and fall profiles with variable mixed-layer depths. The case of downward refraction offers an opportunity to determine bottom properties when coastal eddies and internal wave effects are minimal.

The increase in the understanding of multiparameter inversions has enabled the estimation of bottom properties when a receiving array and a receiver are employed such as in the experiment conducted by Holmes et al. (2006) in an area where the general limits on bottom properties are known. The use of ambient noise as the source of sound for these types of inversions has been demonstrated by the work of Harrison (2002), Siderius (2006), and Harrison (2009). If one were to use this inversion of shallow water inversions in conjunction with an autonomous vehicle towed array, a cost-effective survey method would provide the required information for noise calculations. It must be mentioned that shallow water environments can be broadly characterized by the formation of the sediment layering by processes of deposition, volcanic layering, and glacial activity. Not all shallow water bottoms may be characterized by inversions and in some interesting areas only measurements will suffice.

Correlation Issues

The response of an array of hydrophones in the noise field is known to be determined by the space-time correlation properties of the field. Cron and Sherman (1962) developed expressions for these correlation functions assuming ergodic random noise sources for volumetric (isotropic) generated noise and surface-generated noise (anisotropic) for directional sources. The noise field was composed of multiple frequency-dependent components such as distant shipping-generated and local wind-generated noise. Cox (1973) examined the correlative properties of temporally stationary and spatially homogeneous (ergodic) noise fields. He employed spherical harmonics and their series expansion to describe the cross-spectral density between two sensors and its wavenumber projection. Both formulations were found to agree with experimental measurements and were useful in the optimum spacing of array hydrophones. Ferguson (1987) applied the methods of Cron and Cox to determine the directional response of a horizontal array to the ocean noise field, with favorable comparisons with experimental results.

The noise response of a vertical array in a weakly range dependent shallow water waveguide, an adiabatic channel, was used to estimate surface source levels by Burgess and Kewley (1983). The difference between upward- and downward-directed beams was related to a distribution of random sources at the air–sea interface. This technique was employed by Harrison et al. (2001) to obtain bottom reflectivity. Coherent sources of sound with either a horizontal or a vertical array coupled with synthetic aperture methods have been employed to produce wavenumber spectra and estimates of the propagating modal eigenfunctions and eigenvalues [Holmes (2006)]. These methods can also be refined by the use of model-based recursive processing and sophisticated multiparameter inversions.

The ambient noise research issue is the use of random surface noise sources or the radiated noise from a surface craft to estimate the modal field near a vertical array. Certainly, the excitation of a set of modal eigenfunctions depends on the near-surface source, the receiver depth, and the propagation characteristics of the shallow water channel. In the case of a weakly range dependent waveguide with minimal attenuation, the adiabatic coupling of modes applies and near the array one would expect to find each mode to be the sum of identical modes with random phase. However, the depth variation would simply be that of the modal eigenfunction and the correlation between pairs of hydrophones will reflect the commonality. One could use the approach of Cron and Cox to this problem or one could use the expected modal field and its eigenvalues. The resulting correlation function can then be used to estimate the Green's function kernel.

Snyder (2008) estimated the correlation coefficient of a time series of power estimates from measurements with hydrophones moored at a depth of 2,935 m, a water depth of 3,200 m, and spaced 2.56 and 2.29 km. He used eight 1-Hz frequency bands between 25 and 1,000 Hz. The correlation coefficient increased with frequency and was greater than 0.5 for frequencies greater than 200 Hz, with correlation times on the order of hours. This investigation shows that spatially separated receivers have correlated power spectral estimates consistent with a weakly range dependent waveguide and a stationary random process.

Roux et al. (2005) showed theoretically that Green′s function between two different locations can be estimated by the cross-correlation of the noise field observed at each location. This development assumes an ergodic noise field (stationary and homogeneous medium), adiabatic propagation with minimal attenuation, and mode stripping. Sabra et al. (2005c) also showed that the derivative of the cross-correlation function can be related to the coherent deterministic arrival time. Attenuation was approximated by a perturbed sound speed rather than a complex wavenumber. These studies are an interesting application of ambient noise. It is not clear whether this approach will be feasible in a noise field that is a complex mixture of distance and local sources as well as the frequency dependence of the dispersive waveguide.

Computational Issues

The final issue is the applied ocean physics and applied mathematics task of producing accurate numerical models of an ocean basin assimilated with observational sea surface temperature, current, and bathymetry to provide the basis for range-dependent calculations with distributed sources. The Northeast Pacific calculation shows that such a process is feasible. The issue is the determination of a wave-theoretic transmission calculation to cover the 0.1–10-kHz range that utilizes variable range–depth sampling bandwidths for rapid accurate calculation.

The major problem one faces in such a calculation is the use of multiple high-resolution digital databases, the linkage of this information, and the construction of range-dependent information to be used in the calculation of the sound transmission from the source of noise to the receiver. The calculations that have been performed to date are basically expectation-value calculations and these may be adequate for the higher frequencies, regions where natural mechanisms dominate. But, as seen in Chapter 3, high-resolution arrays observe a two-component noise field, natural noise and dynamic shipping. The degree of resolution in space-time to which this type of computation can or should be extended is an unresolved issue.

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