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MODELING ACOUSTIC PROPAGATION AND SCATTERING IN LITTORAL AREAS

Littoral (near-coastal or shallow) waters are extremely complex environments to model. This article discusses the physical processes that must be considered to accurately model acoustic propagation and scattering in littoral areas and assesses the ability of generic classes of models to represent those processes. No models to date accurately describe acoustic propagation and scattering in littoral areas where the environment is strongly range-dependent, a situation typical in such regions. A discussion of the limitations of existing models, as well as recommendations for gathering information pertinent to the successful development of accurate acoustic prediction codes, is presented. A viable model would provide a cost-effective means of facilitating the design of future shallow-water active and passive acoustic systems and enable an assessment of the performance of potential tactics to be used in littoral areas.

INTRODUCTION

Research on shallow-water acoustics has been conducted for many years by the Navy, but at a low level of effort since no shallow-water threat of any immediate consequence existed. For at least the last twenty-two years, the major research focus has been on deep-water acoustics to counter the Soviet submarine threat and to protect our own ballistic missile submarine force from detection and neutralization. With the collapse of the Soviet Union, however, and the increasing belligerence of Third World powers, future submarine warfare is likely to be conducted in littoral areas. Hence, there arises an urgent need to address shallow-water acoustic propagation and scattering and their relevant physics.

Given a proper understanding of the nature of acoustic propagation in littoral areas, accurate acoustic models may be developed that will enable us to predict propagation and scattering characteristics in any shallow-water region of interest. The utility of such models in, for example, experiment planning and analysis, systems analysis and research, and scenario simulation and war-gaming, would be great, as demonstrated repeatedly in deep-water acoustic research and investigation. With the expected decline in funding for defense-related endeavors, accurate modeling would offer a cost-effective means of helping us design future shallow-water systems and assess the performance and effectiveness of proposed littoral systems and tactics.

Acoustic systems to be employed in littoral areas can be either passive or active. Passive sonar entails listening to or sensing radiated emissions from a potential target (e.g., a submarine). This signal must be detected and discriminated against a background of oceanic ambient noise, caused, for example, by wind–wave activity at the sea surface and by shipping.

In contrast, in an active acoustic system, an acoustic pulse is transmitted, and the returning "echo" from the target is sensed. As in a passive sonar system, the ambient noise background is present, but additional interfering sounds, termed reverberation, are also present. This unwanted acoustic energy results from scattering of the transmitted pulse to the receiver from rough boundaries (sea surface and bottom) and volume inhomogeneities.

Littoral areas are complex environments to model. In the shallow waters of coastal regions and on the continental shelves, the sound-velocity profile is generally irregular and unpredictable and is greatly affected by surface heating and cooling, salinity changes, and water currents. The shallow-water profile is complicated by the influence of salinity changes caused by nearby sources of fresh water and contains many gradient layers with little temporal or spatial stability.[1] The structure of the sediment in the ocean bottom is also very complex, further complicating the nature of the propagation.

Because of the complexity of the shallow-water environment compared with the deep-ocean environment, more extensive environmental measurements must be made to support the modeling effort. Without that supporting environmental data input to the models, any modeling effort will have limited value. The design of future sonar systems based on unvalidated models would clearly be futile. Therefore, good acoustic data, taken concurrently with accurate environmental data, are required to validate any candidate acoustic model.

To put the difficulty of assessing acoustic propagation in shallow water in proper context, we first examine the physics of shallow-water propagation,[2-5] focusing on the physical conditions that must be considered to describe the phenomenon. We then survey the current models and assess how well they take these conditions into account. Finally, we specify the supporting environmental data needed to enhance both our knowledge of shallow-water acoustic propagation and our ability to model it.

PHYSICS OF SHALLOW-WATER PROPAGATION

Let us begin by defining the important concept of transmission loss. Strictly speaking, the instantaneous acoustic intensity $\mathbf{J}$ is defined as

$$\mathbf{J} = p\mathbf{v} \ , \tag{1}$$

where p is the acoustic pressure, and $\mathbf{v}$ is the acoustic particle velocity. Acoustic sensors, which are usually hydrophones, do not measure the particle velocity. Consequently, ocean acousticians take as a measure of the intensity the quantity

$$J = \frac{p^2}{\rho c} , \tag{2}$$

where ρ is the water density, and c is the speed of sound. Equation 2 follows directly from Equation 1 if the wavefront is planar (a usual assumption). The intensity, J, is then averaged over time to obtain

$$I = \frac{1}{T}\int_0^T J \, dt \ . \tag{3}$$

The units of intensity are average power per square meter. Transmission loss (TL) or propagation loss is then defined as

$$\mathrm{TL} = -10 \log \frac{I_r}{I_{1\,\mathrm{m}}} \ , \tag{4}$$

where I_r is the intensity at a range r, and $I_{1\mathrm{m}}$ is the intensity at 1 m from the source.

The conditions influencing shallow-water propagation are as follows:

- Seasonal changes in the water-column sound-velocity profile
- Volume absorption in the water
- Water depth
- Sea-surface roughness
- Bubbles
- Biological scatterers
- Bathymetry (bottom topography)
- Bottom composition (affecting, e.g., compressional sound velocity, compressional absorption, density)
- Shear sound velocity
- Shear absorption
- Bottom interface roughness and sediment volume inhomogeneities

Water only supports a compressional sound wave, a wave in which the particle motion of the medium oscillates in the direction of propagation of the sound wave. The speed of sound in the ocean depends on water temperature, salinity, and pressure. The variation of sound speed from the ocean surface to the bottom cannot be neglected, although the variation of water density is usually neglected. Since the sound speed depends on temperature, it is very sensitive to seasonal changes. Temperature-versus-depth measurements are easy to make at sea; salinity-versus-depth measurements are often ignored in deep-water scenarios, and a constant salinity is used to calculate sound speed. But ignoring salinity gradients in many shallow-water areas can lead to gross errors in the sound-speed profile. Large salinity gradients near the surface can turn a strongly negative temperature gradient into a strongly positive sound-speed gradient directly beneath the surface, forming a surface duct. Because of the positive sound-speed gradient, surface ducts can cause sound energy to be trapped within them owing to upward refraction or to be channeled out of the ducts by leakage if the acoustic frequency is low enough. In either instance, transmission loss can be affected considerably. Such gradients are typical near river outlets.

Absorption losses in a medium may be divided into three basic types: viscous losses, heat conduction losses, and losses associated with molecular exchanges of energy. Viscous losses result when there is relative motion between adjacent portions of the medium, as during the compressions and expansions associated with the passage of a sound wave. Heat conduction losses result from the conduction of heat between the higher-temperature compressions and the lower-temperature expansions of the medium. Viscous and heat conduction losses do not account for the excess absorption in seawater; this excess is caused by molecular exchanges of energy. Two mechanisms of such energy exchange dominate in water: structural relaxation and chemical relaxation processes. Structural relaxation is due to the conversion of kinetic energy into potential energy in the structural rearrangement of adjacent molecules in some clusters; it results from volume changes, not temperature changes, and is measured by the coefficient of volume viscosity. Chemical relaxation is due to the association and disassociation of different ionic species such as magnesium sulfate (above 1 kHz) and boric acid (below 1 kHz).

Water depth is also an important parameter for propagation. Although it is easy to measure, small errors in depth can cause significant errors in transmission loss, particularly at low frequencies due to modal cutoff. Water depth will play an important role in determining the optimum frequency of propagation in a shallow-water waveguide.

Sea-surface roughness can increase transmission loss at higher frequencies and contribute to significant levels of reverberation. The effects of sea-surface roughness are accentuated by the presence of a surface duct. Surface roughness is determined by the sea state; to model the effects of surface roughness, a directional wave-height spectrum is required. Extensive data on wave-height spectra for the deep ocean exist but are not appropriate in shallow water.

Sound may be scattered away from its original path by both bubbles and biological scatterers. The bubble distribution in shallow water can differ from that in deep water. In addition to bubbles caused by wind-wave action, bubbles can also be formed by decaying organic material on the bottom in shallow water. The major biological scatterers at our frequencies of interest are fish, which can be abundant in some shallow-water regions.

Bottom roughness and sediment volume inhomogeneities can also increase transmission loss and reverberation at higher frequencies. We know little about either of these parameters, and both are extremely difficult to measure.

Probably the most important bottom parameter is the speed of compressional sound waves in the surficial sediment. Shallow-water areas are notorious for their spatial variability; a patchwork of bottom types is the rule rather than the exception. Sediment types are determined by the relative amounts of three constituents: sand, silt, and clay. These three terms refer only to the size of the sediment particles and not to composition. Particle diameters range from 2 to 1/16 mm for sand, 1/16 to 1/256 mm for silt, and 1/256 to 1/4096 mm for clay. Compressional wave sound-speed gradients in the sediments are much greater than in the water column. Typical values for sediment gradients are between 0.5 and 2.0 s^{-1}. Also, we must take into account the variation with depth of the absorption of the compressional waves and the sediment density, which we do not have to consider for the water column.

In the sediment—and especially in the hard rock basement beneath the sediment—we encounter a new, complex phenomenon: shear waves. Whereas compressional sound waves can be described by a wave equation for a single scalar function (e.g., the acoustic pressure), shear waves are described by a vector wave equation, usually the vector displacement of the particles due to the passage of the shear wave. A shear wave is a wave in which the material particle can oscillate transversely to the direction of propagation of the wave. The absorption coefficient and speed of a shear wave differ considerably from those for a compressional wave. In sediments, the shear speed varies typically from 250 to 600 m/s. In rock such as basalt, the shear speed is 2500 m/s. In seawater, the compressional speed is about 1500 m/s, whereas in sediments it can vary from 1500 up to 1800 m/s or more.

The conditions noted above affect transmission loss in shallow water in various ways. Figure 1 shows the effect of seasonal changes on propagation under summer and winter conditions.[5] The effect of channel tuning is apparent. For example, in Figure 1A, frequencies around 250 Hz propagate with less loss than other frequencies. Also, propagation is better under winter conditions than summer conditions because the sound-velocity profile in winter (shown to the right of Fig. 1B) has a positive gradient or surface duct that refracts the sound upward away from the bottom. In the summer, when the sound-velocity gradient is negative over much of the depth, the sound is refracted downward and interacts with the bottom, which has a higher attenuation than the water. (Attenuation refers to the loss of energy from the original sound beam due to both absorption and scattering.)

Figure 2 shows the effect of water depth on propagation.[5] As seen in the figure, the greater the water depth, the smaller the losses and the lower the optimum frequency.

Figure 3 shows the acoustic field and an associated bathymetric profile from deep to shallow water.[5] (A potential scenario for an active acoustic system is to position the source in deep water and receivers in both deep water and on the continental shelf.) The figure shows two basic regions: a flat, shallow-water part where a characteristic optimum frequency of around 200 Hz develops under good propagation conditions and a steep slope where the losses increase dramatically and the optimum frequency moves toward lower frequencies owing to the change in water depth.[5]

Figure 4 shows the effect of bottom composition on propagation.[5] Within 60 km from the source, material on the seafloor changes from sand/silt/clay to silty sand and then to sand. The acoustic field demonstrates this composition by an increased optimum propagation frequency over the sandy bottom and by higher losses at low frequencies.[5]

Now let us examine the effect of shear on propagation. Shear can be neglected only for very "soft" sediments in which shear speeds are low (≤200 m/s). In harder, unconsolidated sediments, shear properties are important. To illustrate the effect of shear, we use a set of experimental data collected in shallow water in the Mediterranean Sea. The measured sound-speed profile is shown in

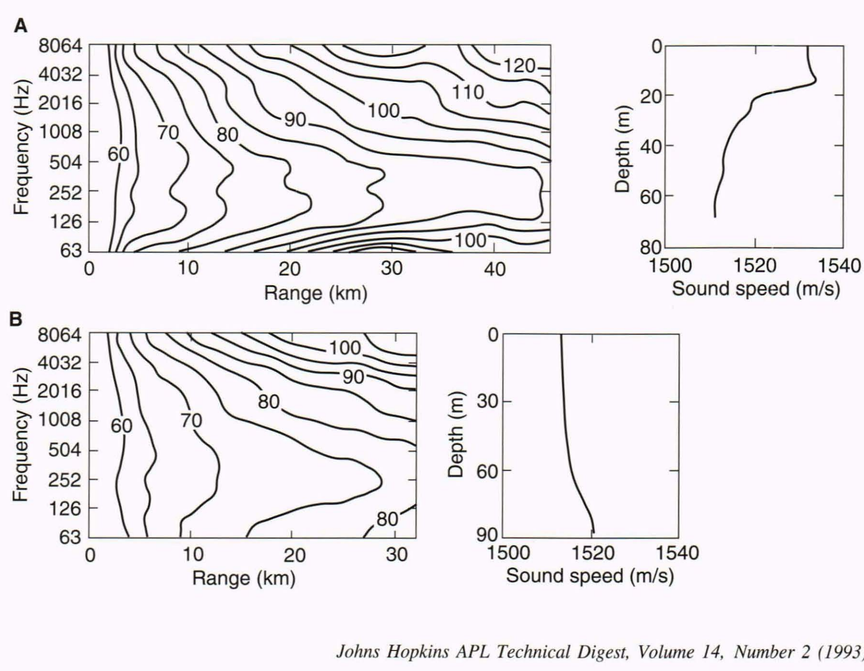


Figure 1. Transmission loss (contours in dB) as a function of frequency and range measured over the same propagation path for different seasons. Source depth is 50 m, and receiver depth is 40 m. **A**. Summer conditions. **B**. Winter conditions. The figures to the right of the transmission loss contours are the corresponding sound-speed profiles. (Reprinted, with permission, from Ref. 5, p. 565, © 1980 by Plenum Press.)

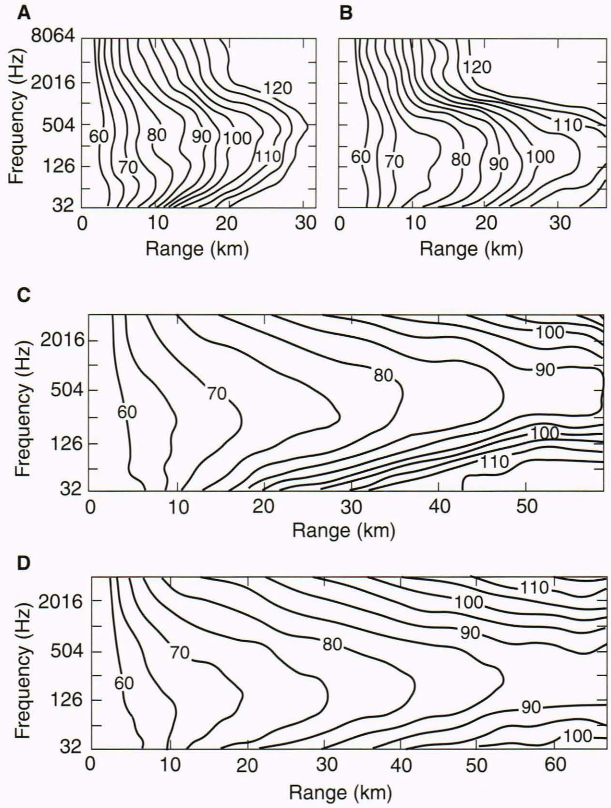


Figure 2. Transmission loss (contours in dB) as a function of frequency and range measured for different water depths. **A.** 50 m. **B.** 90 m. **C.** 120 m. **D.** 300 m. (Reprinted, with permission, from Ref. 5, p. 566, © 1980 by Plenum Press.)

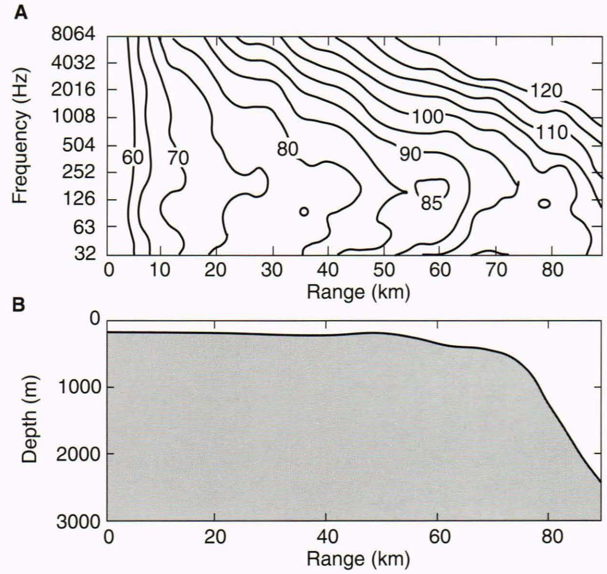


Figure 3. Transmission loss (contours in dB) as a function of frequency and range measured over a continental slope. Source depth is 50 m, and receiver depth is 67 m. **A.** Transmission loss contours. **B.** Bathymetry of continental slope. (Reprinted, with permission, from Ref. 5, p. 569, © 1980 by Plenum Press.)

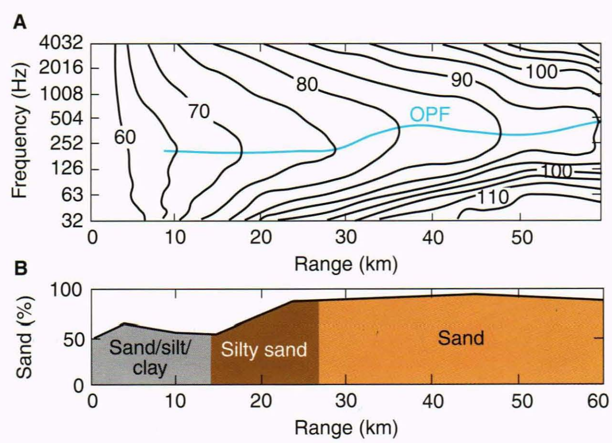


Figure 4. Effect of bottom composition on propagation. **A.** Transmission loss (contours in dB) as a function of frequency and range, measured for different bottom sediments. Blue curve is optimum propagation frequency (OPF). **B.** Composition in bottom sediment as a function of range. (Reprinted, with permission, from Ref. 5, p. 570, © 1980 by Plenum Press.)

Figure 5; the source is at 50 m and the receiver is at 40 m.[3] The water depth is 70 m, and the downward refracting sound-speed profile causes strong sound interaction with the seafloor. The bottom properties used for numerical modeling (primarily sand) are listed in the figure caption.

Figure 6 shows the measured transmission loss at a range of 30 km as a function of frequency.[3] The optimum frequency occurs between 200 and 400 Hz. The figure also presents two theoretical curves calculated by a normal-mode program, one neglecting shear and the other including shear. Shear is an important loss mechanism at all frequencies, even though shear losses are highest at low frequencies, where the sound penetrates deeper into the bottom than at high frequencies. (A second example is discussed later in conjunction with Fig. 13.)

Figure 7 shows the modeled effects of different bottom types on transmission loss versus frequency.[3] For each curve, 100 m of isovelocity water with a sound speed of 1500 m/s overlies a homogeneous sediment whose type and compressional and shear speeds are shown. The source is at 50 m, and the receiver is at 100 m. The transmission loss is measured at a range of 10 km.

Consider the curve for silt. Above 40 Hz we see good propagation with a cutoff at about 10 Hz. At very low frequencies (0.1 to 0.3 Hz), seismic propagation becomes important, and sound propagates as an interface wave along the seafloor. This type of wave has its highest excitation at the water/bottom interface and an exponentially decaying amplitude away from the surface. For the other bottom types we notice that the interface-wave excitation increases with shear speed. The interface wave becomes an integral part of the waterborne spectrum when the shear speed is higher than the speed of sound in water, which is true for basalt.

Significantly, limestone shows the greatest transmission loss since it is a compact material with high density. The loss is not due to high compressional-wave absorption; rather, it occurs because its shear speed is close to

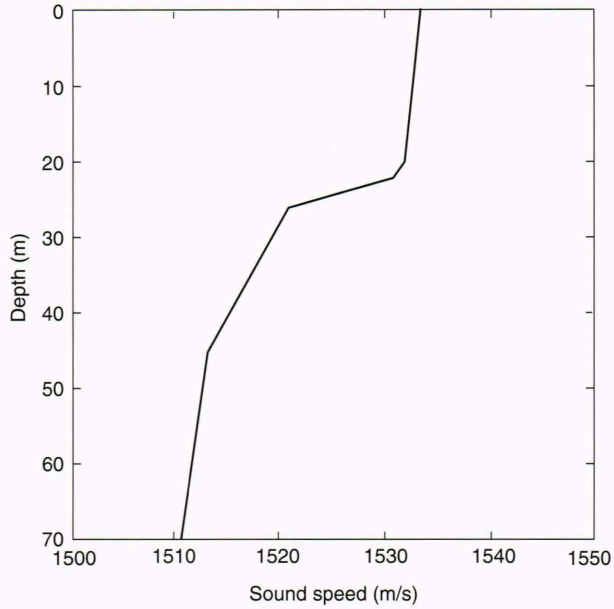


Figure 5. Sound-speed profile for a shallow-water area in the southern Mediterranean. Source depth is 50 m, and receiver depth is 40 m. Bottom properties: compressional sound speed = 1700 m/s; shear sound speed = 500 m/s; compressional attenuation = 0.75 dB/wavelength; shear attenuation = 1.50 dB/wavelength; density = 2 g/cm^3.

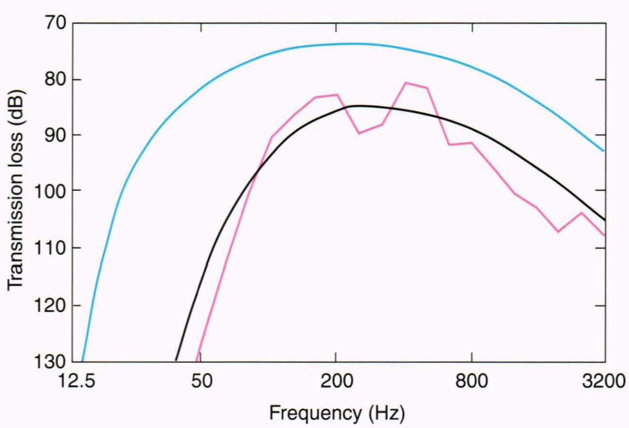


Figure 6. Comparison of measured and computed transmission losses at a range of 30 km. Source depth is 50 m, and receiver depth is 40 m. Blue curve shows theory with no shear; black curve shows theory with shear; and red curve shows measured data.

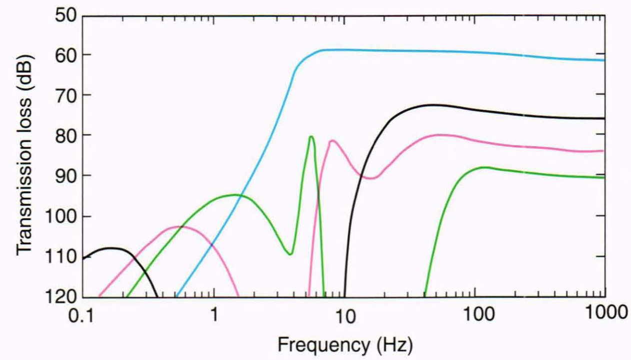


Figure 7. Transmission loss versus frequency for different bottom types at a range of 10 km for a water depth of 100 m. Source depth is 50 m, and receiver depth is 100 m. Blue curve shows basalt (compressional speed, 5250 m/s; shear speed, 2500 m/s). Black curve shows silt (compressional speed, 1600 m/s; shear speed, 200 m/s). Red curve shows sand (compressional speed, 1800 m/s; shear speed, 600 m/s). Green curve shows limestone (compressional speed, 2250 m/s; shear speed, 1000 m/s).

the compressional speed in water, which causes a strong coupling of waterborne energy into shear energy. The shear absorption in limestone is 2.5 times greater than the compressional absorption.

Now let us try to understand the reasons for an optimum frequency in a shallow-water waveguide. The high loss at high frequency results from both the volume absorption and scattering loss at the rough seafloor and from the rough sediment/bedrock interface. These two mechanisms of attenuation monotonically decrease with decreasing frequency. At lower frequency, more interaction with the bottom occurs, and consequently absorption and propagation effects in the bottom become important. Although compressional absorption decreases with decreasing frequency, the overall result on sound propagating in the water column is an increasing loss with decreasing frequency; the dominant effect is the greater penetration of the sound into the bottom as the frequency becomes smaller. The coupling of sound into shear waves increases with increasing bottom interaction, until surface waves at the seafloor become an important propagation path near the cutoff frequency of the water column. The total effect of both compressional- and shear-wave losses in the bottom is an increasing loss for waterborne sound with decreasing frequency. The optimum frequency decreases with increasing water depth because, at a given frequency, the bottom interaction decreases as the water deepens. Consequently, the bottom-loss mechanisms responsible for the existence of the optimum frequency will be dominant at still lower frequencies as water depth increases.[4]

SHALLOW-WATER MODELING

In what follows we will not discuss the details of specific models; rather, we will examine how well generic classes of models take into account the previously described physical processes. These generic classes are ray, range-independent normal-mode, and range-dependent full-wave models (coupled-mode, adiabatic-mode, and parabolic equation models).

At frequencies above 1000 Hz, we may be forced to use ray models no matter how well they work, simply because the computations for a wave model become too complex or time-consuming. At lower frequencies, where we have a choice between ray models and full-wave models, we think it best to use a full-wave model for three reasons. First, at wavelengths that are small in relation to the surface duct thickness, ray theory does not account correctly for the diffraction leakage out of the duct. Second, the ray approximation to wave theory becomes valid only if there are many modes to support the propagation. A ray path can exist only if there are numerous contiguous modes that can coherently combine to create that path. In shallow water at low frequencies, where few modes exist, well-defined ray paths do not exist.

The third reason to use a full-wave model is more complicated. Since shallow-water propagation can involve considerable bottom interaction, ray models must be able to account for such interaction correctly. In the typical ray model (let us call this the standard ray model), the sediment layers are replaced by a single reflecting surface at the water/bottom interface. Bottom interaction is handled by assigning to the bottom specularly reflected ray a bottom-reflection loss. This concept, however, has serious flaws.[6,7]

The interaction of an acoustic signal with a single surface can be described in terms of a single function—the reflection coefficient. Figure 8 shows a typical geoacoustic model that yields the plane-wave reflection coefficient at the water/bottom interface as a function of angle and frequency. This model considers an infinite single-frequency plane wave to be incident at only one angle with the ocean bottom. The bottom is assumed to have smooth, parallel boundaries where the input parameters are layer thickness, density, sound speed, sound-speed gradient, and absorption. The reflection coefficient is defined as the ratio of the reflected to the incident acoustic intensity, and the logarithm of the coefficient is called bottom-reflection loss. To measure bottom-reflection loss within the constraints of this definition is virtually impossible.

A practical approach to the measurement of the bottom-reflection coefficient is to first measure the propagation loss of an acoustic pulse that traverses the medium from source to receiver through the acoustic path that enables the pulse to interact once with only the ocean bottom. The second step is to calculate the water-column propagation loss for only the bottom-reflection path by assuming a flat single-interface bottom having a reflection coefficient of one. The final step is to compare the measured and calculated propagation losses; the difference is known as bottom loss. Because of water-region multipaths, however, considerable care and interpretation are required to determine the transmission loss for the energy that has interacted only with the ocean bottom.

Consider an ideal plane-wave reflection curve as shown in Figure 9, which portrays a critical grazing angle caused by the sound speed of the sediment being greater than that of the water column. Rays that strike the bottom at a grazing angle less than the critical angle will be totally reflected with no loss. Consider also the omnidirectional impulsive point source shown in the figure and an acoustic path where energy impinges on the sediment at a relatively low grazing angle θ_1. On the basis of the plane-wave reflection curve, all energy is reflected. Consider next an acoustic path associated with energy that impinges on the sediment at a higher grazing angle θ_2. This energy penetrates and traverses through the sediment. If a positive sound-speed gradient exists in the sediment (and it usually does), the energy will be refracted and returned to the water at a distance downrange. If the travel time of the refracted energy equals the travel time of the reflected energy at some point in the medium, the arrival interpreted as being only a bottom-reflected arrival will actually contain additional interfering energy from the refracted path.

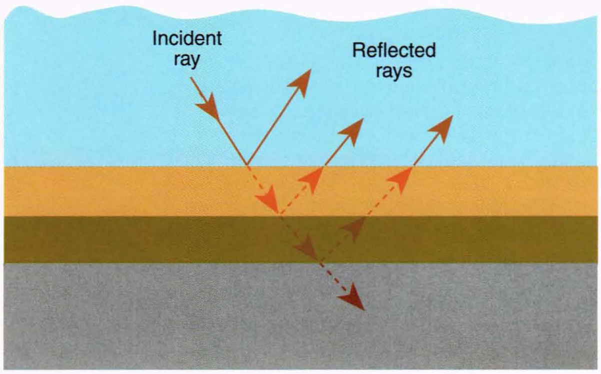


Figure 8. Plane-wave geoacoustic model of the sediment. Blue is water; tan is the first sediment layer; brown is the second sediment layer; and gray is the solid basement.

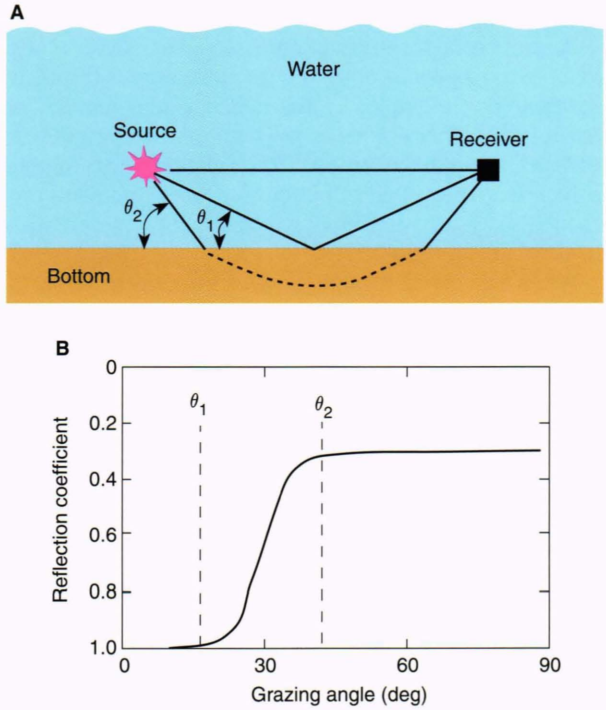
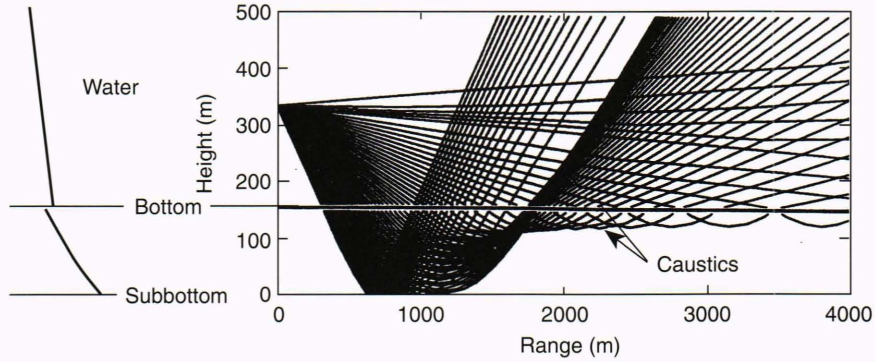


Figure 9. Mechanism causing time-coincident bottom-reflected and -refracted signals. **A.** Ray paths between source and receiver. θ_1 is an incident grazing angle less than the critical angle; θ_2 is an incident grazing angle greater than the critical angle. **B.** Reflection coefficient versus grazing angle.

The Naval Undersea Warfare Center (NUWC) performed an acoustic experiment to demonstrate this result in collaboration with the Lamont-Doherty Geological Observatory, which conducted geoacoustic measurements of the sediments. Figure 10 shows (left) the sound-speed profile in the water column and the sediment and (right) a diagram with rays that penetrate the sediment (standard ray models do not have this feature). The ray diagram

Figure 10. Characteristic water-bottom sound-speed profile (left of figure) and ray diagram (right of figure) showing the formation of caustics due to the refraction of sound in the sediment. Reprinted, with permission, from Frisk, G., "Determination of Sediment Sound Speed Profiles Using Caustic Range Information," in *Bottom-Interacting Ocean Acoustics*, Kuperman, W. A., and Jensen, F. B. (eds.), Plenum Press, New York, p. 154 (1980).



shows the focusing of energy by the ocean bottom and demonstrates that concurrent refracted and reflected arrivals could occur over a considerable volume of the water. When standard experimental techniques were used to determine bottom-reflection loss versus angle, a negative-loss region was observed for some angles (Fig. 11). At least for the angles in the negative-loss region and possibly for other angles as well, an interfering ray path refracted through the bottom. These negative-loss regions (which were prevalent in bottom-loss measurements) remained a mystery until they were explained by scientists at NUWC in the mid-1970s.

When the incident angle is near the critical angle of the water/sediment interface, a lateral surface wave is generated which, upon radiating back to the receiver, cannot be separated from the reflected wave. Thus, one cannot measure the true specularly reflected wave from the water/sediment interface. To analyze the data, one would need a plane-wave model to separate the refracted and lateral waves and so obtain the true water/sediment reflection coefficient. The geoacoustic properties of the bottom would have to be measured. If one has the geoacoustic properties of the bottom, it is better to use a full-wave model, with its fewer approximations. The use of a reflection coefficient in a standard ray model (which does not include a layered bottom) would lead to neglect of the energy in the refracted and lateral waves that is being dumped back into the water column. If the bottom-loss coefficient due to all energy paths were used, it would be difficult to assign an angle to it, and the results obtained would be incorrect.

Range-independent normal-mode models that include shear are good predictors of propagation in a shallow-water range-independent environment if adequate supporting environmental data exist, but few shallow-water sites possess such an environment over any significant range.

Only range-dependent, full-wave, exact-solution models can yield reliable predictions for shallow-water propagation and scattering. Let us call this class of models coupled-mode models and discuss their usefulness.

In shallow water, the number and shape of modes can change with range because of (1) variable bathymetry, (2) change of the sound velocity in the water column with range, (3) change of compressional and shear sound velocities in the sediment with range, (4) variation of the thickness of sediment layers with range, (5) rough sea surface or rough sediment interfaces, and (6) change of the absorption or density in the water or sediment with range. Most shallow-water environments have one or more of these range variations. When the number and shape of modes differ at different ranges, we need a theory to describe how energy can be transferred from mode to mode as it propagates down the wave guide. If mode coupling is ignored, we will see that the transmission loss can be in error by a large amount.

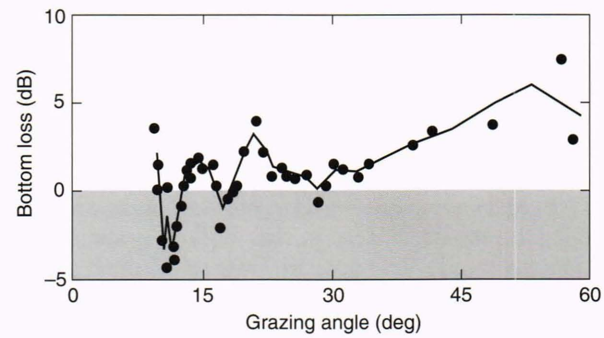


Figure 11. Bottom-loss results versus grazing angle in the 80- to 320-Hz frequency band. The points are measured data. The solid curve is a three-point moving average fit to the data. The shaded area is the negative-loss region.

A coupled-mode model is needed if one wants to study the effect of propagation and scattering on different waveforms to design a sonar processing system. Also, an exact solution using coupled-mode theory is needed to determine how accurately the environmental input data must be known to satisfy the modeling requirements. Otherwise, if a model disagrees with the acoustic data, we do not know whether the error is in the sampling of the coarse environmental data or in the physics of the model.

One coefficient in the wave equation is, of course, the speed of sound, $c(x, y, z)$, where x and y are horizontal range coordinates and z is the vertical coordinate, which is positive downward. The wave equation only has a solution in a spatial domain where $c(x, y, z)$ is continuous. At surfaces of discontinuity, such as the water/sediment interface, certain boundary conditions must be satisfied for the continuation of the solution from one domain to the other. The boundary conditions are that the pressure p and its derivative $(1/\rho)(\partial p/\partial n)$ in the direction of the unit vector $\hat{n}$ that is normal (perpendicular) to the boundary must be continuous across the boundary (ρ is the density).

The boundary condition on the normal derivative is extremely difficult to satisfy for a nonhorizontal boundary. Consequently, an approximate boundary condition that was used in all of the initial coupled-mode models developed was

$$\left(\frac{1}{\rho}\right)\left(\frac{\partial p}{\partial n}\right) \approx \left(\frac{1}{\rho}\right)\left(\frac{\partial p}{\partial z}\right) . \tag{5}$$

The boundary is assumed to have a small enough slope so that the horizontal component of the normal vector to the surface can be neglected. The only consequence of this approximation was thought to be to limit the models to irregular interfaces with small slopes; however, in 1979, Rutherford[8] showed that this condition has far worse consequences than just a small slope approximation. What appeared to be a straightforward application of the approximate boundary condition on the normal derivative for a sloping interface was actually an inconsistent application of it. This finding led to a violation of the conservation of energy, which can contribute a significant error. Unfortunately, many of the models based on Equation 5 are still being used today. Rutherford then developed a coupled-mode model that conserved energy by using first-order perturbation theory applied consistently to the problem. Thus, the only limitation in Rutherford's model is the small slope approximation.

Figure 12 compares Rutherford's model with corrections to a coupled-mode model without the corrections for up-slope propagation where the slope is 2.5°. In an attempt to avoid the nonconservation of energy problem, coupled-mode models in the 1980s used a stair-step approximation to the water/sediment interface so that each segment was flat and the approximate boundary condition (Eq. 5) would hold exactly on that segment. But serious problems exist with this approach. No mode coupling or backscattering can occur on the flat portion of a step. All mode coupling and backscattering will occur

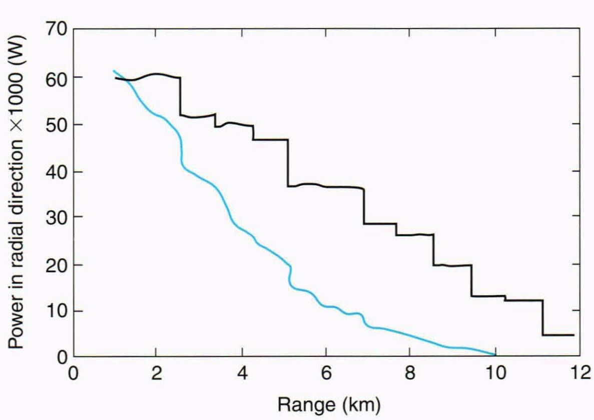


Figure 12. Transmitted power versus range for a coupled-mode theory with corrections (black curve) and without corrections (blue curve). The frequency is 20 Hz and the bottom slope is 2.5°.

at the corners of the step. At the corners, however, the normal derivative to the surface is not defined, and hence the boundary condition does not hold. Moreover, these models represent backscattering from the ocean bottom as backscattering from a series of corners instead of the correct statistical distribution of bottom roughness.

In 1989 and 1992, two coupled-mode models were published that solved the boundary condition on the normal derivative exactly. The first, published by Murphy and Chin-Bing,[9] uses a finite-element technique. The model does not include shear-wave propagation in the sediment. Its major difficulty is that it is computationally slow. The authors say that it can model propagation only at low frequencies and over ranges of several kilometers. Their example uses a 25-Hz source over a 4-km range. The second model, published by Fawcett,[10] also does not include shear and is computationally slow. His example is a waveguide consisting of a homogeneous water column and a homogeneous bottom with an irregular water/bottom interface. He uses a 10-Hz source and computes the propagation to a maximum range of 200 m.

The stair-step models are used today because no other models are available to compute long-range propagation.

The adiabatic approximation to coupled-mode theory neglects all coupling coefficients. This assumption then forces energy within a mode to stay in that mode, on the added assumption that for sufficiently slow range variation of the medium, the effects of mode–mode coupling become small and may therefore be neglected. This uncoupling makes the wave equation much easier to solve. In the adiabatic approximation energy is conserved. In general, however, the adiabatic model is not a useful tool for shallow-water propagation. Rutherford[8] showed that for a clay bottom, mode conversion effects arise for even small slopes between 0.5° and 1.0°, whereas for a sand-bottom mode, conversion effects arise for slopes between 0.06° and 0.6°.

Beebe and McDaniel[11] compared an adiabatic model with shallow-water acoustic data taken off the Scotian shelf in the western North Atlantic Ocean. Figure 13 shows the propagation path and Figure 14 the sound-speed profiles along the track, as well as the receiver array location and source depths. Good environmental data were available for this test site. Data were taken at frequencies of 25, 80, 250, and 800 Hz. At each frequency, data were obtained at three different source depths.

At 25 and 80 Hz, the propagation losses exceeded 100 dB, even at ranges as close as 4 km. At 4 km, the measured losses were over 50 dB greater than those predicted by the model. Beebe and McDaniel attribute this disrepancy to the incorrect modeling of compressional- and shear-wave propagation through the bottom. Figure 15 shows a comparison of measured and modeled propagation losses at 250 Hz for a source depth of 79 m and a receiver depth of 31 m; the agreement is very poor. The authors offer no explanation for this particular comparison. They believe, however, that the disrepancy at 800 Hz could be due to the lack of mode coupling in the adiabatic model. Therefore, the disrepancy at 250 Hz could be attributed to both the lack of mode coupling and significant shear losses.

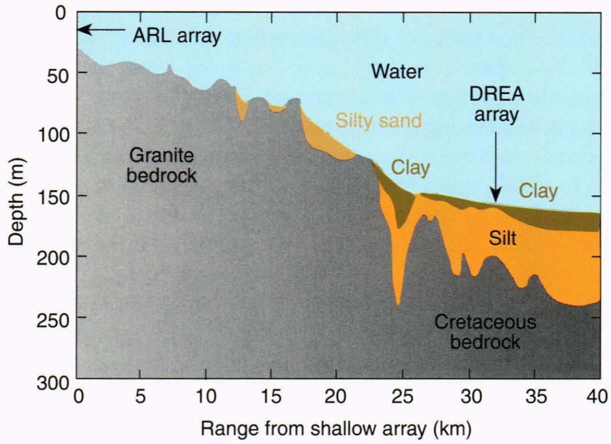


Figure 13. Sediment structure versus range. The horizontal arrow shows the range location of the vertical receiver array belonging to the Pennsylvania State University Applied Research Laboratory (ARL), and the vertical arrow shows the range location of the vertical receiver array belonging to the Defence Research Establishment Atlantic (DREA) of Dartmouth, Nova Scotia. (Reprinted, with permission, from Ref. 11, p. 513, © 1980 by Plenum Press.)

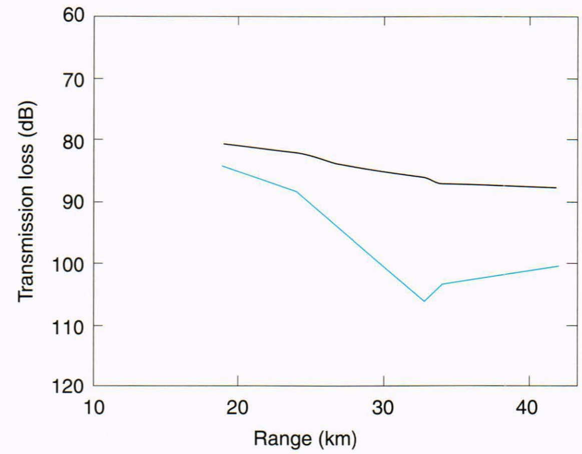


Figure 15. Comparison of experimental data (blue curve) with an adiabatic normal-mode model (black curve) from Ref. 11. Source depth is 79 m, receiver depth is 31 m, and frequency is 250 Hz.

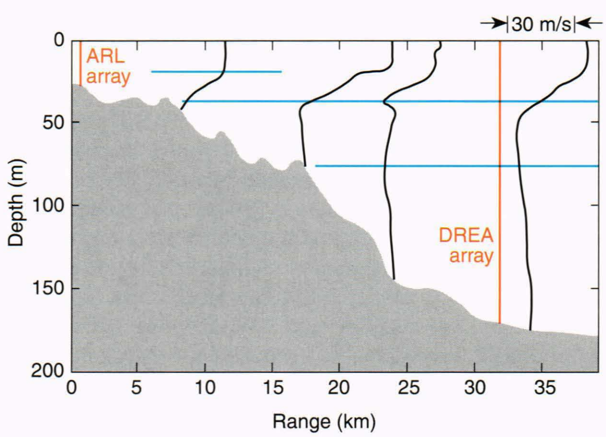


Figure 14. Sound-speed profiles (black curves) and bathymetry versus range. The vertical scale shows depth in meters for the bathymetry curve. The scale at the top right shows meters per second for the sound-speed profile curves superimposed on the bathymetry plot. The locations of the ARL vertical receiver array and the DREA vertical receiver array in Figure 13 are also shown. The blue lines show the ranges and depths employed for the detonation of explosive charges used as sources. (Reprinted, with permission, from Ref. 11, p. 519, © 1980 by Plenum Press.)

A popular class of full-wave models used today is the parabolic equation models: the split-step fast Fourier transform model, the implicit finite-difference model, and the finite-element model.

Let us discuss the implications of the standard parabolic approximation to the wave equation. First, backscattering is neglected, and it is assumed that the environment is slowly varying in range. The parabolic approximation is exact only for the first mode; higher-order modes become progressively less exact. An increasing number of corrections have been added to the parabolic approximation to reduce the error due to the higher-order mode computations. These corrected models are called wide-angle parabolic equation models. For deep-water propagation, where only lower-order modes are needed, the parabolic equation models provide excellent results. For short ranges in shallow water, however, where higher-order mode contributions are appreciable, they can be in error. The parabolic equation solution does include full-mode coupling for the forward-propagating waves in the approximation of no backscatter.

One serious problem with the parabolic equation models for shallow water is that the bottom boundary condition on the normal derivative is incorrect. Just as with the coupled-mode models, some parabolic equation models use the approximate boundary condition given by Equation 5 inconsistently, and the others use a stair-step approximation to the water/sediment interface.

Lee-McCann[12] has published a comparison of an adiabatic-mode model and a wide-angle finite-element parabolic equation model, with transmission loss measured down-slope. A source at a 90-m depth in 150 m of water on the shelf radiated a 50-Hz tonal, and a receiver was towed down-slope to a maximum range of 50 nmi where the water depth reached 1400 m. The adiabatic-mode model was developed by K. J. McCann at the Applied Physics Laboratory, and the finite-element model was developed by M. D. Collins.[13]

Figure 16 shows a ray plot for the case considered. Figure 17 shows a comparison of transmission loss versus range between the adiabatic model and the parabolic equation model. Figure 18 shows a comparison of transmission loss versus range between the adiabatic model and experimental measurements. The adiabatic model fits the data better, particularly at ranges greater than 12 nmi; the adiabatic model, however, best matches the data in the deep basin, but it does not fare as well on the slope.

SUPPORTING ENVIRONMENTAL DATA REQUIREMENTS

Again, shallow-water propagation models could potentially increase our understanding of shallow-water propagation. Such models could also provide a cost-effective and efficient method of assisting in the design and eval-

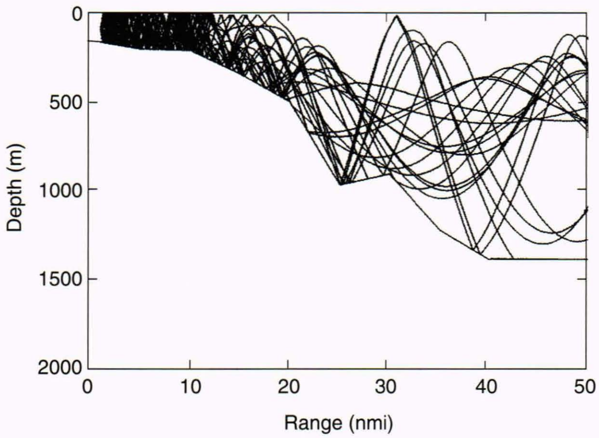


Figure 16. Ray plot from shallow to deep water. Only rays that exit from the source with grazing angles of 10° above or below the horizontal are shown.[12]

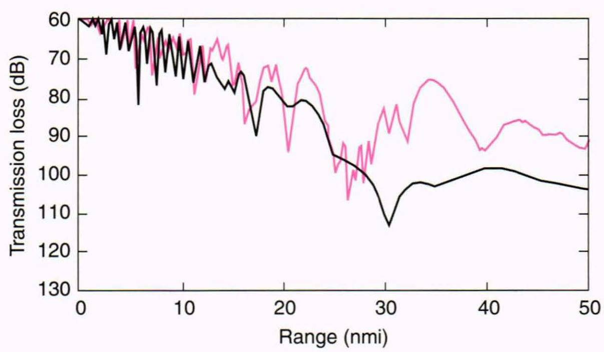


Figure 17. Comparison of transmission loss between an adiabatic normal-mode model (black curve) and a wide-angle finite-element parabolic equation model (red curve). Source depth is 91 m, receiver depth is 120 m, and frequency is 50 Hz.[12]

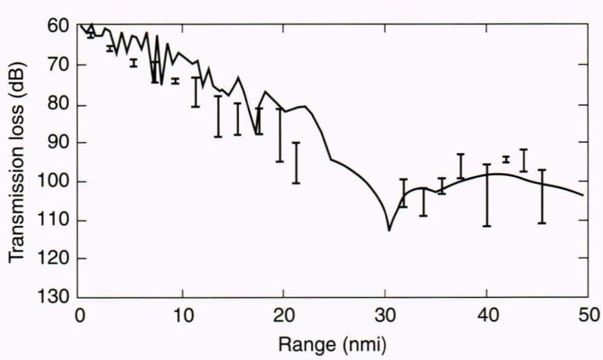


Figure 18. Comparison of measured transmission loss with an adiabatic normal-mode model. The curve is the adiabatic modeled transmission loss taken from Figure 17. The vertical lines show the spread in the experimental data.[12]

uation of future sonar systems operating in shallow water. Therefore, good-quality environmental data must be taken in representative littoral areas, primarily within the local ocean bottom. The minimum data sets that should be obtained are sediment cores, *in situ* velocimeter measurements, chirp sonar measurements, and seismic reflection and refraction measurements.

Although various types of corers exist, the gravity corer, consisting of a long steel (coring) tube, is used most extensively on continental shelves. It can recover vertical sections of sediment as long as 20 m and is driven into the sediment by free fall with additional weight (500 to 1000 kg) attached to the device. The sample, brought to the surface, is contained in a plastic liner that has been inserted into the steel tube before lowering to the bottom.

The physical properties of the sediment are analyzed in the laboratory. The analysis can yield the compressional and shear velocities and corresponding attenuations, bulk density, grain density, porosity, and, of course, sediment classification.

Porosity is defined as the ratio of the volume of voids between the grains in the sediment to the total volume of the sediment aggregate. The grain density is the density of the solid material alone, and the bulk density is the density of the solid material plus water content. The velocities must be corrected to *in situ* conditions; the presence of gas in the sediment, however, complicates this correction when made in the laboratory. To address this problem, the Applied Research Laboratory at the University of Texas has developed a compressional-wave profilometer and a shear transducer that attach to existing coring equipment with minimum modification to that equipment.[14-16] The measurement is made directly as the corer penetrates into the sediment.

The chirp sonar system[17] uses a linearly swept FM pulse over the frequency range of 2 to 10 kHz. The source and receiver arrays are mounted on a tow vehicle designed for profiling at ship speeds of 0 (drifting) to 10 kt. The system has a 10-cm planar resolution and about a 100-m penetration capacity. The acoustic measurement is taken on a track directly below the tow vehicle. The model is calibrated to a local area by using average grain size, grain elasticity, and a rigidity constant obtained from core samples. Measurements then yield the porosity, compressional-wave velocity, rigidity (shear velocity), and bulk density for the top 100 m of the sediment. Compressional and shear attenuations, within the operating frequency band of 2 to 10 kHz, are also obtained.

In marine seismic surveys,[18,19] the acoustic signal starts in the water, reflects or refracts at discontinuities in the bottom and subbottom, and then reenters into the water to the detecting sensors. Seismic systems usually operate between 5 and 200 Hz and can penetrate into the bedrock.

The basic method of measurement is the reflection method, since it is highly efficient in recognizing the structure of layers.[18] This reflective method is shown in Figure 19A.

An alternative method, the refraction method (Fig. 19B), is used to explore discontinuities in the acoustic-velocity profile when a material with higher velocity lies beneath a material with lower velocity. Refracted waves that seismologists call "diving waves" (Fig. 19C) occur if the velocity in the lower medium is increasing continuously with depth.

The most important point in all seismic methods is the high multiplicity of sensor channels, which ensures that

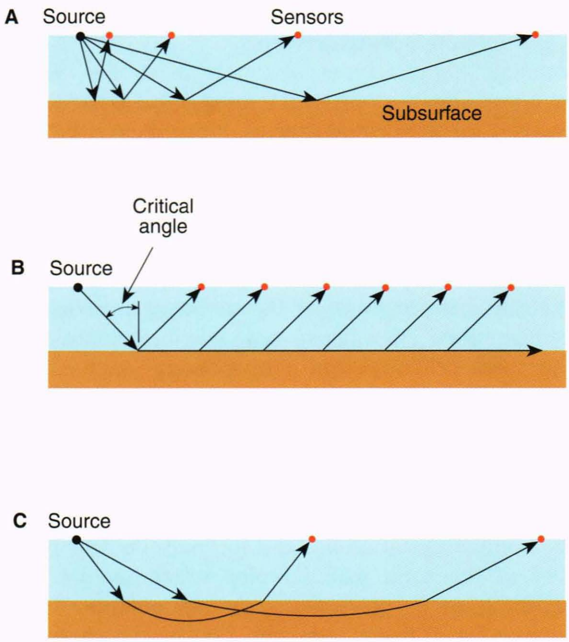


Figure 19. Three seismic techniques for measuring bottom properties. **A.** Rays representing reflected waves. **B.** Rays representing refracted waves. **C.** Rays representing diving waves.

the different types of waves are distinguishable and that the reflectors lost because of poor reflectivity or the high attenuation of the signals can be picked up again.[18] In addition, the redundancy of data allows improvement of the overall signal-to-noise ratio.

Sources can be air guns, water guns, sparkers, or explosive charges. The receivers are typically an array of hydrophones. The best results can be obtained from a long towed array consisting of at least 200 hydrophones, but sonobuoys have at times been used successfully.

Seismic profiling can yield both compressional and shear velocities and compressional and shear attenuations. Of course, such profiling also yields layer thicknesses.

SUMMARY

Today's international political climate is changing dramatically. The collapse of the Soviet Union has eliminated, at least for the moment, the long-range threat that has faced us throughout the Cold War. With the increasing belligerence of emerging Third World nations, and their ability to obtain high-technology weapons, systems, and platforms, the emphasis on defense is shifting to coastal regions. Thus, a comprehensive understanding of this new littoral environment must be expeditiously pursued with the vigor of past deep-water research efforts.

Given the expected decline in the defense budget, we need to focus our research efforts on judiciously selected undertakings with potential payoffs, both short- and long-term. Taking a lesson from previous deep-water research, acoustic modeling may prove a productive and cost-effective means of pursuing scientific research and more system- or scenario-specific investigations. The shallow-water acoustic environment is extremely complex, however, much more so than its deep-water counterpart. Thus, high-quality acoustic measurements must be obtained in regions of interest to increase our knowledge of the local propagation conditions and also to extend our understanding of the physical processes responsible for that propagation. With this understanding, accurate and reliable models can be developed and validated. Although no such models exist, several candidate approaches, most notably the coupled normal-mode treatments, appear promising. Their usefulness and practicality are limited by their severe computational requirements, but advances in computer processing, as well as in mathematical and algorithm development techniques, could make them viable in the near future. In addition, the results of ongoing research efforts might spawn radically different approaches to the acoustic propagation problem in shallow water.

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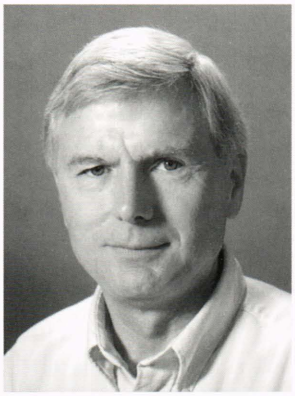
THE AUTHORS



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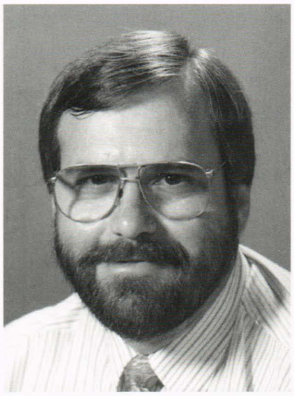

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