Acoustical oceanography in the coastal environment

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Abstract

Acoustical oceanography in coastal waters depends on coupled ocean acoustical models that include current flows, surface gravity waves, internal waves and bubbles. One of the main modeling issues in shallow coastal waters is the reverberant environment that complicates the interpretation of acoustic transmissions. These factors are illustrated with a Doppler sonar model that includes multi-path reverberation and wave trough-shadowing. The model is used to derive some performance limits of sonars operated in the surf zone.

1. Introduction

Since the ocean is largely opaque to all but the lowest frequency electromagnetic radiation, sound waves have been used extensively to study a diverse set of ocean phenomena over a wide range of length and time scales. The term 'acoustical oceanography' in its broadest sense refers to the use of sound in the ocean to study ocean processes, and encompasses the use of Doppler sonars, tomographic arrays, acoustical bubble sensors and passive tomography, which is the use of ambient noise to study the ocean environment. Even restricting attention to the coastal environment, a review of such a broad field is not possible here, and the interested reader is referred to Clay and Medwin [1], Robinson and Lee [2], and Munk, Worcester and Wunsch [3] for an introduction to this field.

The central theme of this paper is an illustration of some of the problems associated with inverting the properties of long range sound transmissions in coastal waters for the underlying oceanography. Here, the term 'long range' means horizontal distances greater than about ten water depths. As pointed out by Robinson and Lee [2],

> "Now is a unique time in the history of acoustical oceanography. Physical oceanography has just achieved the knowledge, technical base, and models necessary to provide the environmental fields for realistic ocean acoustic propagation on a substantial basis... Research on the coupling of ocean dynamical and acoustical models is timely and important."

The observable metrics of sound transmission, such as arrival time, amplitude, phase, Doppler shift, multi-path scattering and so on are usually affected by more than a single environmental factor, and coupled ocean dynamical and acoustical models are essential to the interpretation of these signals. Thus success in solving the inversion problem, i.e. determining the ocean environment from the sound field, is based on two things: first, an ability to solve the forward transmission problem, and, second, on some existing knowledge of prevailing oceanography. This point will be discussed in the context of coastal acoustic tomography, a maturing field with a growing body of literature, and surf zone acoustics. The challenges to interpreting long range sound transmissions are particularly severe in the surf zone where bubbles, wave-induced currents and boundary scattering all affect the sound field, and the very shallow water geometry makes it difficult to separate these effects.

A discussion of coastal acoustic tomography can be found in section 2. Long range tomography in this context implies the use of acoustic frequencies from order 100 to 1000 Hz, and takes place over 1000's of meters. Bathymetry, sediment properties and water column properties, such as sound speed profiles and internal waves, are important environmental factors. In section 3, we move to the surf zone and consider the performance of acoustic Doppler sonars. This work builds on the results of Smith [4] who has considered the performance of Doppler sonars in the surf zone (also see Gallagher *et al.* [5]). Some results from a new model for sonar performance at frequencies of 10 to 100 kHz and over ranges of 100's of meters are presented. The effects of multi-path reverberation, wave crest shadowing and the spatial distributions of microbubbles on sonar performance are discussed. The concluding remarks can be found in section 4.

2. Coastal Acoustic Tomography

Coastal acoustic tomography is the shallow water analogue of the deep water technique introduced by Munk and Wunsch in 1979[6]. The underlying idea is to use the travel time of acoustic pulses propagating through a region of interest to map both coastal circulation and the ocean's thermal structure. The scientific and engineering problems stem from the fact that shallow water ranges of interest typically lead to arrivals closely spaced in time, making them difficult to resolve and track with single hydrophone systems. The basic signal processing and modeling issues have been discussed by Miller, Ching-Sang Chiu and Lynch [7, 8]. The problem of tracking individual arrivals in shallow water can be resolved by using both temporal processing of phase-modulated, maximal-length acoustic pulses and spatial beamforming with vertical hydrophone arrays. These processing schemes have been applied to data collected in the Barents Sea [9] in 100 to 400 m deep water to derive ray arrival time versus angle and mode arrival time versus mode number across a 1.3 km path. This data was used by Chiu *et al.* [8] to map a vertical slice of the Barents Sea Polar Front using a hybrid ray/mode inverse method. This work was continued with two additional publications detailing a coupled-mode propagation model [10] and the effect of shallow-water internal waves and internal tides on travel-time perturbations [11]. This seminal work demonstrates that coastal acoustic tomography can yield detailed estimates of the evolving temperature field in the water column. It also highlights the problems associated with interpreting acoustic transmissions complicated by the superposition of multiple environmental effects. Acoustic travel-time perturbations, for example, are induced by the evolving temperature field, internal waves and internal tides (see Lynch *et al.* [11] and, more recently, Finette *et al.* [12] and the references therein). In addition, the tomographic inversions take the form of perturbations from a 'reference' ocean obtained from conductivity and temperature casts, emphasizing the need for *a priori* information about the prevailing oceanography.

In their paper, Chiu *et al.* note the sensitivity of propagation model results to sediment geoacoustic properties [10]. This sensitivity did not pose a problem for the Barents Sea experiment because the sediment layer was thin and has little effect on the low order modes used for the tomographic inversions. However, when the sediment layer is sufficiently thick, the group speed dispersion properties of the shallow water wave guide can be used to determine the sediment compressional wave speed as a function of range and depth (see Potty *et al.* [13], Lynch *et al.* [14], Tolstoy [15, 16] and the references therein, for example).

In addition to these active inversions, where sound has been created in the water with either sources or explosive charges, there is a growing interest in using ambient noise for passive tomography (sometimes called ambient noise oceanography). In shallow water, the vertical directionality and coherence of the time-averaged ambient noise field are relatively stable features that depend on the compressional and shear wave speeds of the sea floor. This structure has been exploited to invert ambient noise data for the geoacoustic properties of the sea floor at the Cortez Bank, a raised bank of volcanic origin 90 nautical miles from Pt. Loma, California, and the North Celtic Sea [17]. These kinds of studies encounter the same difficulties as active tomographic methods: the coupling of environmental effects complicates the estimation of environmental properties. That this is so for passive tomography is illustrated by the deep water, theoretical study of Perkins *et al.* [18], who showed that the location of ocean mesoscale features could be determined by the coherent processing of ambient noise data on several multi-dimensional arrays.

The final example of passive tomography comes from the surf zone. The noise from breaking surf, when observed on the seaward side of the surf, appears to radiate from compact regions at the ends of the breaking wave crest [19]. This effect is caused by the interaction between the sound radiated by the breaking wave crest and the large population of bubbles left in the water column behind the wave crest. The bubbly region absorbs the sound from all but the very ends of the breaking crest, resulting in the formation of "acoustic hot-spots" [20]. This structure is evident in the horizontal directionality of the noise field which can be inverted to yield estimates of the wave break-point trajectory through the surf zone. Thus simultaneous measurement of the incident wave field and noise field directionality would allow the connection between wave height, bottom bathymetry and the formation of break points to be studied.

3. Characterizing near-shore processes with acoustic Doppler sonars.

Some spectacular images of coastal processes obtained with Doppler sonars have been presented [21-24], and Smith [4] has considered the performance of Doppler sonars in the surf zone. However, a detailed acoustical model for the interaction of sonar signals with the surf zone environment is not yet established, and the beginnings of such a model are presented here. The main objective of this section is to illustrate how the coupling between sound, environment and instrument performance can be studied with a propagation model, and to simplify matters I have restricted attention to a series of specific environmental effects. Within this context, the model might seem overly simplistic; those readers interested in a more comprehensive treatment of the problem are referred to Deane *et al.* [21].

The objective for calculating Doppler sonar performance is to estimate the properties of sound pulses backscattered by microbubbles or other Lagrange tracers in the water column. Typically, both target strength and water velocity as a function of range can be estimated from the backscattered signal amplitude and phase. In shallow water, the interpretation of backscattered signals is complicated by multi-path reverberation, which allows the possibility of sound scattered from different ranges and populations of targets to arrive at the receiver simultaneously. Signal backscattered from the sea surface and seafloor, and absorption by suspended sediments [25] and microbubbles [26] needs to be accounted for. In the surf zone, where wave heights reach a significant fraction of the total water depth, the possibility of wave troughs casting an 'acoustic shadow' on wave crests also needs to be addressed. These effects are illustrated by the cartoon in Figure 1, which shows wave fronts propagating shoreward in the near-shore region. Signals are scattered from the water column boundaries, absorbed and scattered by suspended sediment and microbubbles in the water column and blocked by surface gravity wave troughs. Signal backscattered from targets in the water column propagates back to the sonar transducer through a similar environment.

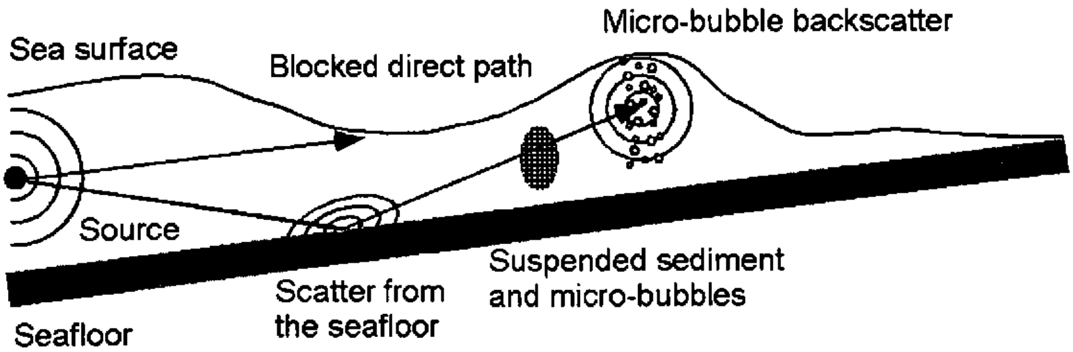

Figure 1. A cartoon of propagation through the surf zone

Notwithstanding these effects, horizontally-oriented Doppler sonars have been shown to yield quantitative estimates of near-shore circulation and the shoaling surface gravity wave field [4, 21-24]. Our objective here is to demonstrate some of the principles of acoustical oceanography in shallow water by calculating the performance limits of Doppler sonars pointed horizontally shoreward beyond the surf zone. The simplest model is considered. The acoustic wavelength of sonar pulses is assumed to be small compared with surface gravity wave scales and water depth, attenuation due to suspended sediment and microbubbles and backscatter from the sea floor are not accounted for (on the grounds that they do not affect the specific phenomena we are interested in), and two dimensional propagation is assumed.

As a starting point for an acoustical model, the ocean surface and seafloor are assumed to be flat so that the sonar signals propagate through a wedge. With the assumption that reflection from the sea floor results in an amplitude change only, a time-domain form of propagation through the wedge can be written as a sum of source images (Brekhovskikh and Lysanov [27]). Each image represents a reverberant path of wave fronts scattered between the surface and seafloor, and can be identified with a 'generating sequence' that specifies the order of boundary reflections taken by acoustic wave fronts as they propagate from the source to the elemental volume of interest in the water column [28]. The set of generating sequences contributing to the sound field is denoted by Ξ, which contains all the images on the image circle between the horizontal and the critical grazing angle of the sea floor. The time-varying pressure field p_b at a range $\mathbf{r}_b$ from the wedge apex (vectors appear in bold type) can be written as

$$p_b(\mathbf{r}_b,t)=\sum_{\Lambda\in\Xi}\frac{S^{ns(\Lambda)}B^{nb(\Lambda)}}{R_\Lambda}p_s(t-R_\Lambda/c), \qquad (1)$$

where S and B respectively are the reflection coefficients for the surface and sea floor, $ns(\Lambda)$ and $nb(\Lambda)$ respectively are the number of surface and bottom reflections in the generating sequence Λ, $p_s(t)$ is the amplitude of the pressure wave generated by the source, as a function of time t, R_Λ is the total path length for wave fronts from the image Λ, and c is the speed of sound. The sum on the right hand side of (1) represents time-delayed signal replicas, each weighted by geometrical spreading and the losses that occur at boundary interactions. The distance R_Λ between the source image associated with Λ and the scattering volume determines both the time delay and geometrical spreading of the acoustic arrival. Equation (1) neglects the absorption of sound by suspended sediment and microbubbles, and any refraction associated with bubble-induced sound speed variations. As discussed by Richards *et al.* [25], these phenomena influence sonar performance, but have been neglected here in favor of boundary reverberation and the effects of the surface wave field. This neglect is justified on the grounds that although refraction and absorption will alter the details of the multi-path arrival structure of the sonar pulse, the effects of range-smearing and wave-crest shadowing are controlled by reflection and absorption by the seabed and surface boundaries, and do not depend critically on the details of the propagation paths followed by wave fronts. A notable exception to this argument is the absorption that occurs immediately after a breaking wave and the formation of a wall of bubbles that can completely block the forward transmission of sound (see, for example, Figures 13 and 14 of Smith [4]). However, we do not need to be concerned with the details of absorption within the bubble wall as it defines the operational shoreward limit of the sonar.

Each image contribution in (1) results in a set Ξ of backscattered paths, and the backscattered signal from a small volume element of bubbles in the water column can be written as a double sum of Doppler-shifted, time-delayed signal replicas:

$$dq(\mathbf{r}_b) = dV \sum_{\tilde{\Lambda}\in\Xi} \frac{S^{ns(\tilde{\Lambda})} B^{nb(\tilde{\Lambda})}}{R_{\tilde{\Lambda}}} \sigma(\mathbf{r}_b) \sum_{\Lambda\in\Xi} \frac{S^{ns(\Lambda)} B^{nb(\Lambda)}}{R_{\Lambda}} D\left(p_s(t - R_{\Lambda}/c - R_{\tilde{\Lambda}}/c), \Lambda, \tilde{\Lambda}, \mathbf{v}_b\right), \tag{2}$$

where $\sigma(\mathbf{r}_b)$ is the scattering strength of the micro bubbles in the scattering volume dV, $D(p(t), \Lambda, \tilde{\Lambda}, \mathbf{v}_b)$ is the Doppler-shifted, scattered pulse, which is a function of the incident and return paths and the scattering volume velocity $\mathbf{v}_b$, $ns(\tilde{\Lambda})$, $nb(\tilde{\Lambda})$ and $R_{\tilde{\Lambda}}$ respectively are the number of surface and bottom interactions and the path length of the backscatter path $\tilde{\Lambda}$. Each Doppler-shifted replica has a total round-trip time delay of

$$\tau_{\Lambda,\tilde{\Lambda}} = \frac{R_{\Lambda} + R_{\tilde{\Lambda}}}{c}. \tag{3}$$

Equation (2) is an acoustical model for the reverberant, backscattered signal at the sonar. It neglects the effects of absorption by suspended sediments and microbubbles in the water column, and backscatter from the surface and seafloor. As discussed above, absorption is not an important determinant of range-smearing or wave-crest shadowing. In his review of boundary scattering limitations on sonar performance, Trevorrow [29] concludes that surface backscatter can be neglected, but bottom backscatter can be a source of bias. As noted by Smith [4], surface activity generates a sufficient density of micro bubbles to generate sonar returns on the seaward side of the breaking zone when the wind speed is greater than about 4 m/s but under dead calm conditions bottom backscatter could dominate the returned sonar signal. The analysis presented here is predicated on the assumption that there are sufficient bubbles present in the water column to dominate backscatter from the sea floor.

3.1 Range smearing

Equation (3) defines the time delay of a Doppler-shifted acoustic pulse, incident along the path Λ and scattered along the path $\tilde{\Lambda}$. All wave fronts with the same delay arrive at the sonar transceiver simultaneously, and thus all contribute to the velocity estimated from the mean Doppler shift. The scattering volumes that generate simultaneous arrivals for a given arrival and return path lie on a locus defined by:

$$R_{\Lambda} + R_{\tilde{\Lambda}} = 2\mathrm{R}_0, \tag{4}$$

where R_0 is a chosen, constant path length. For the special case of the direct arrival and direct return (no surface or bottom reflections), (4) describes a circle, but in general the solution is an ellipse, with foci at the source images Λ and $\tilde{\Lambda}$.

Examples of the constant-time-delay ellipses are shown in Figure 2. The wedge angle has been exaggerated in the example to spread the source images on the image circle. Two constant-time-delay ellipses are shown: I is the circle associated with the direct path arrival and return and II corresponds to an arrival and return at the critical grazing angle. These are the limiting loci, which respectively represent the most distant and closest scattering elements that generate simultaneous arrivals at the sonar. An approximate expression for the scaled range $\Gamma = L/r_s$, where L is the horizontal extent of scattering volumes that generate simultaneous arrivals for a given time delay and r_s is the distance from the wedge apex to the sonar source, can be derived from geometrical arguments and is given by [21]

$$\Gamma = \frac{\theta_c^2}{4} \beta(1-\beta), \tag{5}$$

where $\beta = R_0/r_s$ is the scaled path length. Equation (5) defines the range resolution limit of horizontally oriented, fan-beam Doppler sonars operated in the surf zone. The function Γ attains a maximum at $\beta = 0.5$ so that the range spreading caused by reverberation is greatest half way between the sonar and the apex of the wedge. In addition, Γ scales with the square of the critical grazing angle and so depends on the acoustical properties of the sea floor. Note, however, that the scaled range spread does not depend on the wedge angle. The range smearing that occurs 200 m from a sonar mounted 400 m from shore operating over a medium grained sand with a critical grazing angle of 32 degrees is about 7.8 m.

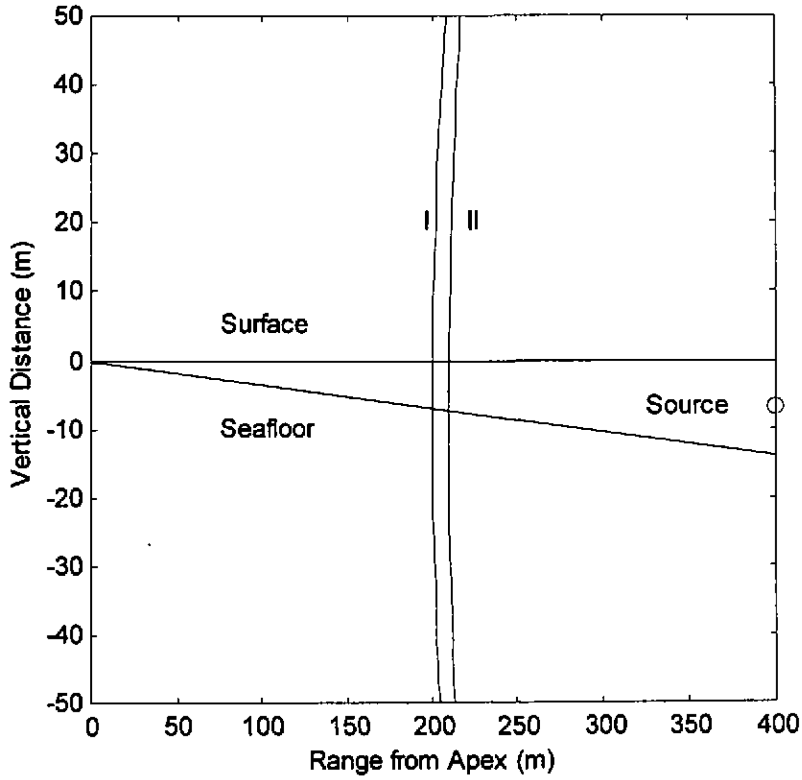

Figure 2. The range limits of scattering volumes that generate simultaneous arrivals from around 200 m

3.2 Wave crest shadowing

Figure 1 shows an example of wave crest shadowing. The wave trough preceding the backscatter targets in the wave crest blocks the direct path signal from the sonar. In this case, the high-angle reverberation responsible for the range smearing discussed above is beneficial because it provides a means of insonifying the wave crests. The grazing angle that reverberant arrivals must exceed to insonify the wave crest depends on the details of the surface wave field, the position of the scattering volume and water depth. However, it is always less than or equal to the maximum slope of the water surface between the wave trough and crest, which is about 10 degrees for a typical wave field (not shown here). Thus wave crest shadowing is not expected to be a dominating factor in surf zone sonar performance, provided that the critical angle of the sea floor somewhat exceeds the maximum wave field surface slope, a condition that might not be satisfied for muddy or silty bottoms, but will be met for medium and coarse grained sands. The shadowing effect is accommodated in the backscatter equation by limiting the sum to images that lie between the critical angle of the sea floor and the maximum slope of the water surface.

3.3 The vertical distribution of scattering particles

Inspection of (2) shows that the returned sonar signal is a function of the backscatter strength of the targets populating the water column. Thus at first consideration, it might seem that the horizontal velocity estimated from the return signal phase shift will be sensitive to the vertical distribution of microbubbles bubbles, which are subject to the effects of dissolution, advection and buoyancy, and which in turn depend on any surfactants present, dissolved gas concentrations, surface and wave-induced boundary layer turbulence, and long-shore and off-shore currents. The effects of these forces on micro-bubbles in the surf zone is a complicated subject (see the discussions by Smith [4], Terrill [30], Vagle *et. al.*[26] and Farmer *et. al.*[24]) and results in a highly heterogeneous and time-dependent distribution. Fortunately, we do not need to be overly concerned with the details of this distribution to obtain a first-order description of sonar performance. The reason is that there is little vertical shear in the horizontal velocity field under the shallow water gravity waves. The first-order relationship between the free surface elevation and the horizontal water velocity for a harmonic, progressive wave as a function of depth below the still water surface is given by the linear, shallow-water equation:

$$u = \frac{H\omega}{2}\frac{\cosh(k_w h + k_w z)}{\sinh(k_w h)}, \tag{6}$$

where H is the trough-to-peak wave height, ω is the angular frequency of the wave, k_w is the wave number of the surface gravity wave, h is the still water depth and z is depth measured upwards from the still water surface. The depth-dependence of the velocity is governed by the $\cosh(k_w h + k_w z)$ term, the variation of which depends on the ratio of the total water depth to wavelength. This is a small number in the surf zone, typically less than 0.1 in 5 m of water, resulting in predicted variations in the horizontal velocity of less than 20% over the vertical extent of the water column. It follows that the velocity estimate is not substantially biased if the Doppler-shifted backscatter occurs preferentially at a particular depth. This is clearly a simplification, and least likely to be true in the region of wave crests where nonlinear effects cause waves to become steeper. However, to first order the water column velocity measurements can be considered insensitive to the details of the microbubble distributions.

4. Concluding Remarks

Acoustical oceanography in shallow, coastal waters is a synthesis of the fields of underwater acoustics and physical oceanography. The problem of interpreting acoustic signals in the presence of strong boundary scattering and currents is heavily dependent on *a priori* knowledge of water column and boundary dynamics, and the availability of coupled acoustical-oceanographic models. This situation is seemingly unavoidable; the application and interpretation of acoustic signals to probe the ocean environment can only be understood with accurate models for the interaction of sound with the environment under study and some existing information about the physical oceanography of the environment.

This point is illustrated by considering the performance of the acoustic Doppler sonar in the surf zone. Two performance issues of interest, range smearing and wave crest shadowing, can be analyzed in terms of a canonical model for propagation. Range smearing sets a fundamental limit to the range resolution of horizontally oriented, fan beam sonars that is a function of the critical angle of the sea floor, but independent of beach slope. Wave crest shadowing, which at first consideration might seem to be a limiting factor, is ameliorated by high angle reverberation provided the critical angle of the seafloor exceeds 20 degrees or so. Some knowledge of shallow water wave mechanics (see (6)) can be used to demonstrate that Doppler sonar velocity estimates are, to first order, insensitive to the spatial distributions of microbubbles that generate backscattered sound.

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