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Over the past decade, advances in the areas of propagation and rough surface scattering have made attractive the concept of generating hybrid models to investigate the impact of realistic two dimensional sea surface roughness on long range acoustic propagation. The development of such models requires that efficient and accurate coupling schemes be created. In this paper, one aspect of this coupling problem is discussed; generating a suitable representation of the incident field for input into the scattering model.

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AN APPROXIMATE TECHNIQUE FOR EXTRACTING THE SURFACE REFLECTED PLANE WAVE SPECTRUM FROM CERTAIN ACOUSTIC PROPAGATION MODELS

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ABSTRACT

Over the past decade, advances in the areas of propagation and rough surface scattering have made attractive the concept of generating hybrid models to investigate the impact of realistic two dimensional sea surface roughness on long range acoustic propagation. The development of such models requires that efficient and accurate coupling schemes be created. In this paper, one aspect of this coupling problem is discussed; generating a suitable representation of the incident field for input into the scattering model.

KEYWORDS

Hybrid models; plane-wave spectrum; scattering; propagation

INTRODUCTION

In the past, one of the standard simplifications applied to the problem of modeling the transmission of sound through an ocean waveguide has been to treat the air/sea interface as a perfectly flat pressure-release (Neumann B.C.) surface. In this approximation, the redistribution of energy that results from the acoustic interaction with the sometimes quite rough sea surface is ignored. On the other hand, researchers interested in the underwater acoustic scattering from a rough sea surface have generally simplified their world by neglecting propagation effects that result from a depth and range-dependent index of refraction. In the last decade, there have been significant advances in the modeling capability for these two aspects of the underwater acoustics problem and, just as important, there has been a tremendous increase in computing power available to researchers and modelers. In fact, much of the work that needs to be done now centers around the creation of hybrid models that can take advantage of advances in both of these modeling areas. Such hybrid models could, for example, be used to explore the effect of different sea-state conditions on long-range propagation. A significant difference between the technique pursued in this paper and some previous approaches (Bucker, 1970; Head et al., 1989) is that this approach allows for the redistribution of the energy due to the scattering where it occurs in space rather than treating the scattering as a simple loss mechanism averaged over range.

Hybrid models of the type alluded to make use of existing propagation and scattering models and are (in the simplest sense) based on coupling schemes that perform two different functions. The first function is to determine from the propagation model that part of the acoustic field that interacts with the boundary of interest and to express it in a form that the scattering model can accept. The second function is to coherently couple the resulting scattered field to the propagating field. While both aspects of the problem are equally important and must be addressed, in this paper, the focus is on a numerically efficient technique aimed at accomplishing the former. In particular, the technique described is appropriate for any propagation model that can provide the complex acoustic pressure field in depth at specified ranges from the source and any deterministic scattering model that can take as input a description of the incident field in terms of plane waves. This technique, which essentially estimates the arrival structure or plane wave spectrum (PWS) incident on a particular patch of an assumed flat ocean surface, provides precisely the information generally required as input to typical scattering models. The organization of this paper is as follows: first, the technique

used to extract the PWS from the propagation model is explained. Next, a benchmark solution for the total surface reflected field is developed from normal mode theory. Finally a numerical example is considered the results of which allow for the verification of two different aspects of the PWS extraction technique; the angular distribution and the total energy reflected from the sea surface versus range.

PWS EXTRACTION TECHNIQUE

For most deterministic and stochastic scattering models the necessary input information typically consists of some description of the pressure field incident on the scattering patch as well as some deterministic or statistical description of the surface roughness. Restricting the discussion to the problem of scattering from a deterministically known surface, it is clear that what the coupling technique must provide to the scattering model is the magnitude and phase for each of the multipaths incident on the particular patch of interest. A particularly convenient description of this arrival structure is in terms of its plane wave spectrum (PWS). Here the PWS is defined to consist of the magnitudes and relative phases of the plane waves incident on a particular patch of the ocean.

The approach employed here to estimate the PWS from the solution of the one-way wave equation is based on the observation that the difference in the vertical energy spectral densities between two nearby ranges, r_1 and r_2

$$D(r_1, r_2, s) = P(r_2, s) \cdot P^*(r_2, s) - P(r_1, s) \cdot P^*(r_1, s), \quad r_2 > r_1, \quad (1)$$

has a clear interpretation in terms changes in the vertical energy distribution of the forward propagated field or, equivalently, in the redirection of energy flow between r_1 and r_2 . Here $P(r, s)$ is the Discrete Fourier Transform (DFT) in z ($\Delta s = 1/(N\Delta z)$) of the pressure field $p(r, z)$. In a typical deep water ocean environment, $D(r_1, r_2, s)$ will be dominated by refraction from within the water column and ocean bottom, reflections and diffractions from bathymetric features, and reflection from the assumed flat sea surface. Of course, $D(r_1, r_2, s)$ will also include the effects of attenuation but this can be assumed to be negligible provided r_2 is not too much larger than r_1 . Of the mechanisms noted, it is clear that plane wave reflections from the sea surface has a distinct signature in the transform space that may be exploited for this particular problem.

Consider a plane wave having traveling upward (vertical wavenumber $k_z = 2\pi s$) in a homogeneous waveguide and reflecting from a finite, mirror-like sea surface centered between r_1 and r_2 . The energy redistribution due to the reflection from the surface (ignoring edge effects) is characterized by a net loss of upward going energy in the vertical energy spectrum at wavenumber k_z and a equal gain of energy at wavenumber $-k_z$. In a more realistic underwater environment where the index of refraction varies with depth only, energy that refracts between two close ranges has the characteristic that the flow of energy is from k_z (upward) to $k_z - \Delta k_z$ for downward refraction or to $k_z + \Delta k_z$ for upward refraction. Thus, it is clear that except for the case where energy is incident at shallow grazing angles (k_z small, $k_z \approx \Delta k_z$), the energy redistribution associated with a reflection from a flat sea surface is easily distinguished from energy traveling in the upward direction that is refracted downward near the surface or elsewhere in the waveguide. Furthermore, the ambiguity that occurs at shallow grazing angles can be minimized simply by forcing r_1 and r_2 closer together. As a practical point, this ambiguity need not be resolved entirely since, except for the roughest of sea surfaces, if a reflection is detected when none occurs the effect of scattering from such extremely low grazing angles is typically insignificant.

Finally, it is noted that the diffractions and reflections that result from bathymetric features can be excluded from the energy spectral density estimates simply by employing a suitable depth dependent filter. A filter of this sort also ensures that the generally upward refraction taking place in the lower half of the waveguide and the generally downward refraction of energy in the upper half of the waveguide do not act together in such a way as to provide the distinct signature associated with a reflection from the sea surface.

The above discussion suggests the following algorithm for extracting the PWS reflected from the sea surface between two ranges r_1 and r_2 :

- 1) Determine difference in the energy spectrum as in Eq. 1 after applying a depth dependent filter that cuts on several acoustic wavelengths below the sea surface.

2) For each positive value of the vertical wavenumber (defined here to be upward) test if $D(k_z) < 0$, and $D(-k_z) > 0$. Only these wavenumbers qualify as potential surface reflections

3) Since some energy imbalance is bound to occur due impart to the truncation of the arrays estimate the reflected energy to be the minimum of $D(k_z)$ and $D(-k_z)$. Normalize the associated amplitude by dividing by $r_2 - r_1$ to get the intensity of the plane wave.

4) The grazing angle associated with this plane wave is $\theta = \arcsin(c \cdot k_z / (2 \cdot \pi \cdot f))$, where c is the sound speed at the surface and f is the acoustic frequency. The relative phase of the plane wave is estimated to be the phase (in that k_z bin) given by the transform of the vertical pressures at r_1

In the following section, a benchmark solution for the total reflected field at the sea surface is developed.

NORMAL MODE THEORY FOR THE SURFACE REFLECTED FIELD

The acoustic pressure in a range independent ocean waveguide can be expressed in a normal mode representation. Using the separation of variables technique to solve the wave equation, we obtain a depth and range dependent part. The normal mode portion $Z_n(z)$ (vertical eigenfunction) is the solution of the following depth equation

$$\rho(z) \frac{d}{dz} \left(\rho^{-1}(z) \frac{dZ_n(z)}{dz} \right) + \left(\frac{\omega^2}{c^2(z)} - \kappa_n^2 \right) Z_n(z) = 0 \quad (2)$$

where $\rho(z)$ is the density of the medium, ω is the angular frequency of the cylindrically spreading wave, $c(z)$ is the compressional sound speed of the medium and κ_n is the horizontal wavenumber or eigenvalue. When assuming that the waveguide consists of many isovelocity sound speed layers, the eigenfunction is expressed as

$$Z_n(z) = A_n \sin(\gamma_n z) + B_n \cos(\gamma_n z) \quad (3)$$

where γ_n is the vertical wavenumber / eigenvalue. The solution to the range equation:

$$\frac{\partial^2 R(r)}{\partial r^2} + \frac{1}{r} \frac{\partial R(r)}{\partial r} + \kappa_n^2 R(r) = 0 \quad (4)$$

is the cylindrical Bessel function of the first kind $J_0(\kappa_n r)$ which, considering only the outgoing wave and large arguments, takes the following form

$$R(r) = \frac{1}{\sqrt{2\pi\kappa_n r}} \left[e^{-i\left(\kappa_n r - \frac{\pi}{4}\right)} \right] \quad (5)$$

Since the depth eigenfunctions are orthogonal, (and are required to be orthonormal) they can be used to expand a particular dependence of pressure on z as a sum of the eigenfunctions. For this case the function is a point source at $r=0$, $z=z_s$:

$$\delta(z - z_s) = \sum_{n=1}^{\infty} Q_n Z_n(z) \quad (6)$$

where Q_n are constants to be determined. Multiplying both sides by $Z_m(z)$ and integrating yields:

$$\rho_0 \int_0^{\infty} Z_m(z) \delta(z - z_s) dz = \sum_n Q_n \rho_0 \int_0^{\infty} Z_m(z) Z_n(z) dz \quad (7)$$

which reduces to

$$\rho_0 Z_m(z_1) = Q_m \Phi_m$$

where

$$\Phi_m = \rho_0 \int_0^\infty Z_m^2(z) dz$$

Finally, we have

$$Q_m = \frac{\rho_0 Z_m(z_1)}{\Phi_m}$$

The sound pressure for the point source becomes

$$P(r, z) = C \sum_m \frac{Z_m(z_1) Z_m(z)}{\Phi_m} \frac{e^{-i(\kappa_m r)}}{\sqrt{\kappa_m r}} \quad (11)$$

where C is a complex numerical constant. In the top layer of the ocean, the boundary conditions require that the coefficients of the cosine term in Eq. 3 vanish. The remaining sine term which can then be expressed in terms of exponentials allows the sum over normal modes to be rewritten as a sum of up and down going plane waves. The surface reflected pressure field is determined by throwing away the downward going plane waves and evaluating the remainder at the surface ($z = 0$),

$$P_{ref}(r) = \frac{-iC}{2} \sum_m \frac{Z_m(z_1) A_m}{\Phi_m} \frac{e^{-i(\kappa_m r)}}{\sqrt{\kappa_m r}} \quad (12)$$

NUMERICAL EXAMPLE/BENCHMARKING

The particular PE model employed for this numerical example was developed at NOARL (Collins, 1988). Several journal articles have been written about this model and no attempt will be made here to review this large body of work. The PE approach (Tappert, 1977) is widely regarded as being accurate and efficient for long-range propagation at low to moderate frequencies. Again, for the purposes of this paper, it is sufficient to point out that the essential attribute of the PE model, in terms of the implementation of the PWS extraction technique, is its ability to produce the complex pressure field as a function of depth at specified ranges.

In this section, a numerical experiment is described and two independent theories are invoked to benchmark or test the PWS extraction technique. The range-independent ocean environment considered in this example has a depth-dependent sound speed profile (the Munk profile) and a cw source operating at 250 Hz located at a depth of 212 m. The waveguide is 3000 m deep below which is 15 m of sediment followed by an isovelocity half space which includes the standard attenuation ramp. A contour plot of transmission loss as calculated by the PE model for this environment is shown in Figure 1. Note that in addition to the convergence zone which starts at approximately 40 km, some strong high angle energy from bottom bounce paths appear to reach the sea surface beginning at about 10 km and ending at about 40 km. A ray trace (not shown) indicates that these bottom bounce paths and other multiple bounce paths contribute to the field at the surface at all ranges.

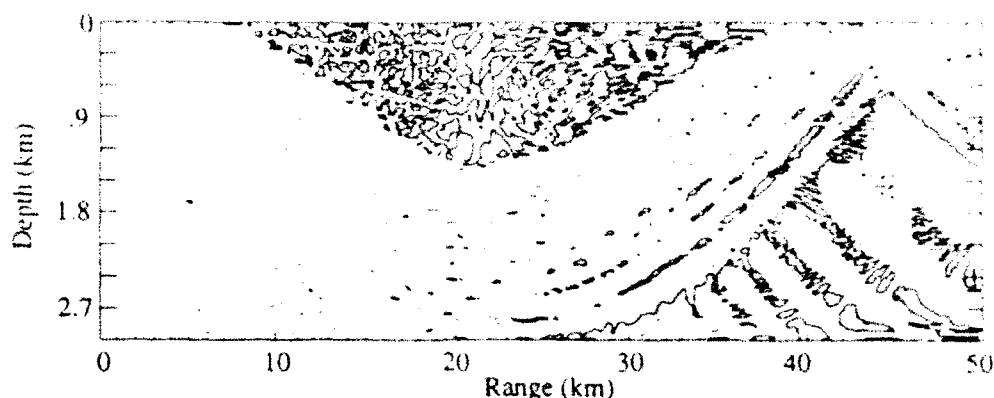


Fig. 1 Contour plot of transmission loss at 93 dB for benchmark problem.

As mentioned earlier, there are two aspects of the PE-extracted surface-reflected PWS that are conveniently tested. First, the total reflected intensity from any particular patch of the ocean surface can be calculated from normal mode theory just described. In Figure 2, a comparison of the total reflected intensity calculated by summing over the surface-reflected PWS and from the normal mode theory for the reflected intensity (derived from Eq. 12) are compared. For this comparison, the vertical filter cut on at a depth of 50 m, the range separation between the two arrays ($r_2 - r_1$) was 2 PE range steps (10 m in this case), and a 1024 FFT was performed. It is clear that both in level and in character the two predictions, particularly from 20 to 50 km, are in agreement. While more significant differences can be noted at ranges closer to the source, it should be noted that these differences are primarily due to the differences in how PE and normal mode models treat a layered environment. Other comparisons (not shown) with a PE based spectral decomposition technique (Norton and Keiffer, 1991) for the same environment show very good agreement at all ranges. In general, both techniques show an initial rapid fall off in reflected energy then a leveling off followed by an increase near where the convergence zone occurs. In the convergence zone the agreement is particularly good. Clearly the main features in these predictions correspond quite closely to the near-surface propagation indicated in Fig. 1.

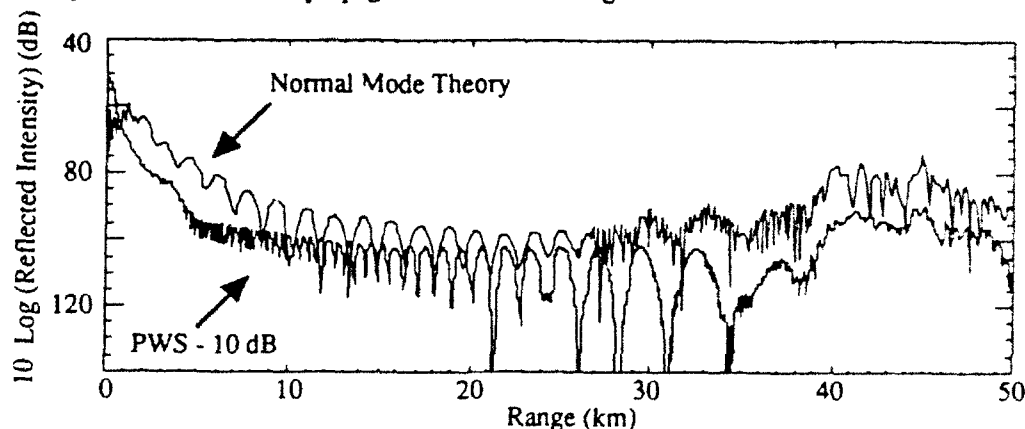


Fig. 2 Comparison of total surface-reflected intensity from PWS extraction technique and from normal mode theory.

Now that it has been verified that the surface-reflected PWS extraction technique yields the correct reflected intensity as a function of range, ray theory is employed to verify that the angular distribution of the reflected energy as a function of range is also correct. There are three regions that can be identified from Fig. 1 that can be clearly associated with different dominant propagation paths. Region 1 extends from the source to approximately 5 km and is identified with direct paths to the surface. In this region the PWS extraction techniques predicts essentially equal contributions to the reflected intensity from all angles very close to the source, by 2 km the contribution is limited to 15 deg. and bottom bounce paths appearing at very high angles begin to become significant. At a range of 5 km the direct path is limited to 3 - 4 deg. and immediately beyond 5 km this path abruptly cuts off (precisely as predicted by ray theory). This begins Region 2 which is characterized

by the dominance of bottom bounce paths. As the range is increased the bottom bounce paths come in at progressively shallower angles (again in agreement with the ray traces) until about 40 km where the convergence zone begins. In this third region, two paths dominate rays initially launched downward at shallow angles that just miss the bottom and those that undergo some interaction with the bottom. In addition there are rays that turn very near the surface in this region. It is precisely the need to distinguish this latter set of rays from those that actually do interact with the surface that makes looking at PWS at two range separated short array an attractive idea.

SUMMARY

A technique has been described that can extract from certain underwater propagation models an estimate of the acoustic field incident on the sea surface in terms of the PWS. This is useful as input to scattering models and thus comprises one part of a coupling scheme that would allow for the generation of hybrid propagation/scattering models. In benchmarking tests, the PWS extraction technique is shown to provide both the correct reflected energy and the correct angular dependence.

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