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## THE OPTIMUM FREQUENCY OF PROPAGATION IN SHALLOW-WATER ENVIRONMENTS

by

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# THE OPTIMUM FREQUENCY OF PROPAGATION IN SHALLOW-WATER ENVIRONMENTS

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# Optimum frequency of propagation in shallow water environments

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The optimum frequency of propagation in shallow-water environments is the result of competing propagation and attenuation mechanisms at high and low frequencies. It is shown that the optimum frequency is strongly dependent on water depth, that it has some dependence on the sound-speed profile, while it is only weakly dependent on the bottom type. A comparison between experimental data and normal-mode theory indicates the importance of shear waves in the bottom, both in determining the optimum frequency of propagation and in determining the actual propagation-loss levels at lower frequencies.

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## INTRODUCTION

There is always an optimum frequency associated with ducted propagation in the ocean. Here we shall attempt to isolate and identify the fundamental mechanisms that determine the optimum frequency of propagation. Both normal-mode theory and a comparison between theory and data will be used in this study.

Figure 1 identifies the three types of sound propagation ducts in the ocean for a typical sound-speed profile. Duct A, which is a bottom-limited duct, is essentially a waveguide bounded by the ocean surface and bottom. It is an important duct for low-frequency deep-water propagation and for coastal or shallow-water propagation in general. Duct B is a surface duct and therefore a waveguide whose lower boundary is determined by the sound-speed profile. The deep sound channel, duct C, is a waveguide where both boundaries are determined by the sound-speed profile.

This paper will be concerned with duct-A type propagation in shallow water environments, which is highly dependent on water depth, season, and bottom type. One can, though, address deep-water optimum-frequency propagation associated with ducts B and C, using similar methods. For duct B it will usually turn out that the optimum frequency is close to the cutoff frequency of the waveguide. Duct C will have an optimum frequency of propagation where the first few modes are trapped above the critical depth and hence do not significantly interact with the bottom. We find an optimal frequency for SOFAR duct propagation of the order of 50 Hz, see also Kibblewhite and Denham.[1] For the low-frequency deep-water duct A, we again have essentially a (scaled) shallow water problem though without significant seasonal effects. (The few hundred hertz optimum frequency that we discuss below for shallow water environments scales to the order of 10 Hz in deep water.)

In Sec. I we present some experimental data together with theory to explain the frequency dependence of sound propagation over a homogeneous bottom. In Sec. II we attempt to isolate the particular mechanisms[2] that determine the optimum frequency for various bottom types, water depths, and seasons, which we do by a combined theoretical and experimental scaling-normalization procedure. In the last section we summarize the results by examining optimum frequency and "optimum range" as functions of season, water depth, and bottom type.

## I. THE EXISTENCE OF AN OPTIMUM FREQUENCY

To illustrate the main features that contribute to the determination of the optimum frequency, we present in this section a comparison between experiment and normal-mode theory. It is generally accepted that normal-mode theory does explain the general properties of sound propagating in shallow water. This has been demonstrated using both cw techniques[3–7] and wideband methods[8–13] for a variety of environmental conditions including cases where bottom rigidity was found to be an important loss mechanism.[5,10,11] The particular data discussed in this section were taken in a coastal area of the North Atlantic in the summer. The data were obtained from experiments using two ships: the receiving ship was anchored with a suspended vertical array covering most of the water column, while the source ship steamed out in range dropping 180-g explosive charges. The experiments were performed over a relatively constant 125-m water depth; the source and receiver locations are shown in Fig. 2 together with the profile and bottom properties. From cores, the bottom appeared homogeneous and sidescan sonar indi-

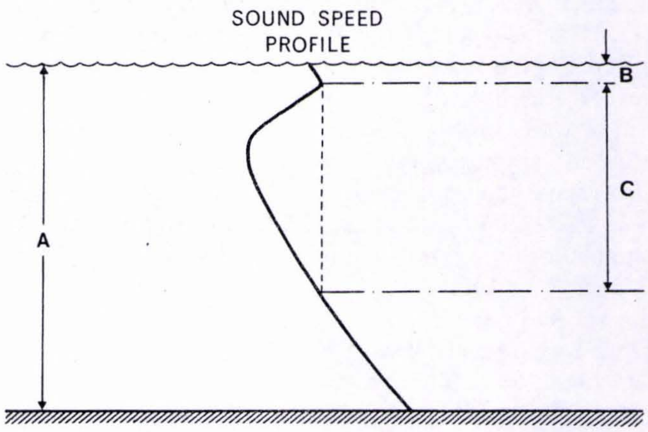


FIG. 1. Sound propagation ducts in the ocean. (A) Bottom-limited duct; (B) Surface duct; (C) Deep sound channel.

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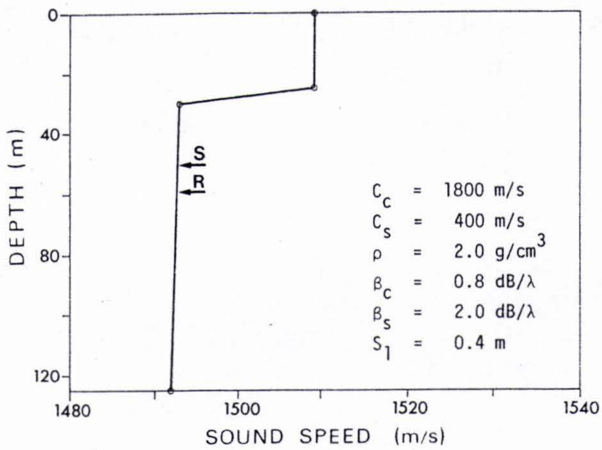


FIG. 2. Sound-speed profile and bottom properties for shallow-water area in the eastern North Atlantic. $C$ = sound speed, $\rho$ = density, $\beta$ = attenuation, $S_1$ = rms bottom roughness, subscripts $c$ and $s$ refer to compressional and shear waves, respectively. Source and receiver depths are indicated on the sound-speed profile.

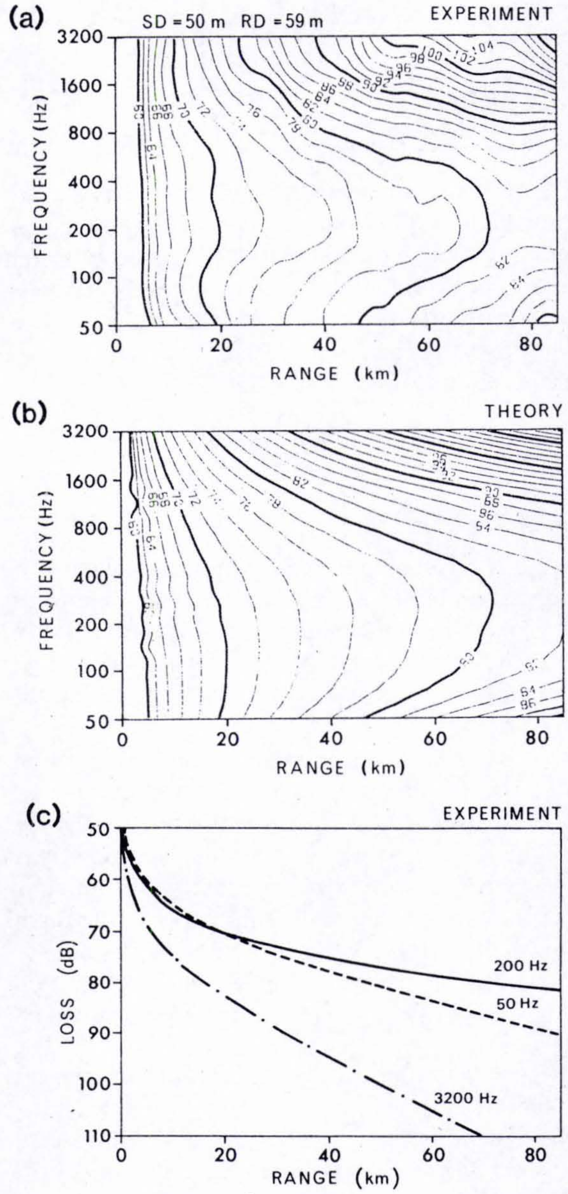


FIG. 3. Propagation loss versus range and frequency from the eastern North Atlantic. (a) Broadband experimental data; (b) Theory; (c) Experimental data at selected frequencies.

cated a prevalence of sand dunes from which we estimated the bottom roughness. The compressional speed and the density were measured from cores. Below we discuss how we obtained the shear speed and the compressional attenuation of the bottom. The shear attenuation was estimated from the literature[14] though this parameter has very little effect on sound propagation in the water column.

The experimental results are displayed in Fig. 3(a) as propagation loss contours versus frequency and range. That is, the more familiar propagation loss versus range curves are retrieved from this type of plot by making a horizontal cut at the frequency of interest. This is shown in Fig. 3(c) where three loss curves resulted from making the appropriate horizontal cuts through the contours of Fig. 3(a). We see from these data that there is an optimum frequency of propagation around 200 Hz; that is, we notice, for example, that the 80-dB contour level in Fig. 3(a) extends out to long ranges at this frequency. We also see that at, say 70 km, there is a sharp increase of propagation loss above and below the optimum frequency. Hence, the contour representation as in Fig. 3(a) not only contains a complete family of propagation loss curves but it is also a very useful visualization of propagation conditions. Figure 3(b) shows the normal-mode result[15] for the environment described in Fig. 2. Here we are contouring the levels of the field calculated from an incoherent summation of modes; it has previously been demonstrated that for shallow-water propagation such an incoherent summation results in an averaging that is equivalent to the experimental third-octave band processing.[13] The effect of low-velocity shear waves on propagation has been included in the modal computations by perturbing the boundary conditions at the sea floor.[5]

The shear speed and compressional attenuation were chosen so as to match theory and data. These two parameters affect the results in different ways. The existence of shear in the bottom is essentially a low-frequency mechanism to carry sound away from the water column through coupling between compressional waves and shear waves in the bottom, and it therefore appears as an attenuation factor for waterborne sound.[5,16] The inclusion of shear was necessary to obtain the correct optimum frequency (compressional attenuation alone would predict too low an optimum frequency and the higher the shear speed, the higher the optimum frequency). Again, we emphasize that shear-wave propagation in the bottom and compressional attenuation have a different frequency-dependent influence on the acoustic field in the water column. The values obtained for the shear speed and the compressional attenuation in the bottom are consistent with the literature (see Sec. II). The agreement between data and theory is to within about 3 dB over 6 octaves of frequency and 85 km of range.

Let us now briefly identify all of the mechanisms used to explain the results in Fig. 3. The high loss at high frequency is comprised of both volume attenuation and scattering

TABLE I. Geoacoustic parameters for different bottom types.

| Bottom type | Porosity $P(\%)$ | Relative density $\rho_b/\rho_w$ | Relative speed $C_b/C_w$ | Compressional speed $C_b$(m/s)[a] | Shear speed $C_s$(m/s) | Compressional attenuation $\beta_c$(dB/$\lambda$) | Shear attenuation $\beta_s$(dB/$\lambda$) |
|---|---|---|---|---|---|---|---|
| Clay–silt | 60 | 1.6 | 1.01 | 1515 | 100 | 0.5 | 1.0 |
| Sand–silt–clay | 55 | 1.7 | 1.02 | 1530 | 150 | 0.8 | 1.5 |
| Silt | 50 | 1.8 | 1.05 | 1575 | 200 | 1.0 | 2.0 |
| Sand–silt | 40 | 1.9 | 1.1 | 1650 | 400 | 0.8 | 1.5 |
| Coarse sand | 35 | 2.0 | 1.2 | 1800 | 600 | 0.7 | 1.5 |
| Chalk–limestone | ... | 2.2 | 1.5 | 2250 | 1000 | 0.4 | 1.0 |
| Limestone | ... | 2.4 | 2.0 | 3000 | 1500 | 0.3 | 0.5 |
| Basalt | ... | 2.6 | 3.5 | 5250 | 2500 | 0.2 | 0.5 |

[a] $C_w = 1500$ m/s.

loss[17] at the rough sea floor (sand dunes). As we go down in frequency these two attenuation mechanisms monotonically decrease. At lower frequency we begin to have more interaction with the bottom and consequently attenuation and propagation effects in the bottom become important loss mechanisms for waterborne sound. First, we have compressional attenuation in the bottom. Even though this attenuation (in dB/m) decreases with frequency, the overall effect on sound propagation in the water column is an increasing loss with decreasing frequency because the dominant effect is the greater penetration into the bottom with decreasing frequency. Second, the excitation of shear waves in the bottom provides the sound field with another degree of freedom to leave the water column. The coupling of sound into shear waves increases with increasing bottom interaction (decreasing frequency), at least until surface waves at the sea floor become important propagation paths near the cutoff frequency of the water duct. The total effect of both compressional-wave attenuation and shear-wave excitation in the bottom is an increasing loss for waterborne sound with decreasing frequency. In Fig. 3 we see the turn-around in the curve (80–dB line) at around 200 Hz. In order to get both the correct levels and the correct optimum frequency we needed the compressional attenuation and shear-speed values shown in Fig. 2, which were essentially determined by trial and error within the constraints of what is found in the literature given the measured core properties: compressional sound speed, density, and porosity. Actually, we feel that it is precisely this type of wideband data–theory comparison that ultimately yields the average acoustic properties of the bottom over a long range in shallow water.

To sum up, we have used an example of data and theory that demonstrates and explains the existence of the optimum frequency in shallow water propagation. In the next section we try to generalize our understanding to different bottom types, water depths, and seasons.

## II. DEPENDENCE OF OPTIMUM FREQUENCY ON BOTTOM TYPE, SEASON, AND WATER DEPTH

In order to investigate the effect of bottom type on the optimum frequency we had to exclude propagation data taken over a significantly layered bottom, since the problem then becomes too complicated[13,16] for the scaling procedure employed in this study. Hence, the results presented below are for a homogeneous bottom, by which we mean that small fluctuations in bottom properties versus depth and range as measured by core analysis and seismic profiling had no significant effect on computed propagation losses. We also know from previous studies[18,19] that only bottom properties to a depth of a few wavelengths affect long-distance shallow-water propagation. Though layered bottoms are excluded, this study is valuable for two reasons: first, by keeping the study as simple as possible the fundamental physical mechanisms are more evident, and second, we know from the existence of data discussed here and elsewhere[6,10] that shallow-water areas with homogeneous bottoms do exist in many areas.

In order to pursue this study, we needed to characterize the ocean bottom by its relevant physical parameters; Table I is a summary of this effort taken from the literature.[20,21] We have listed bottom types according to decreasing porosity (increasing density) and then tried to find representative values for both compressional and shear speeds and for associated attenuation coefficients from the literature. It is well established that both compressional and shear speeds of a sediment increase with density. However, the relationship between the two speeds ($C_b$ and $C_s$) is not a simple function of density. The values given in Table I for $C_b$ and $C_s$ are

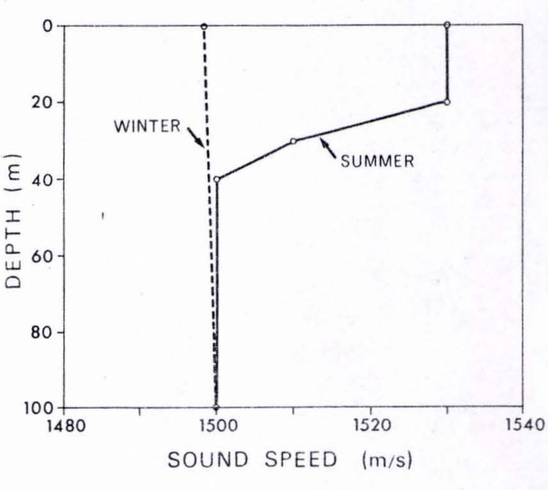


FIG. 4. Typical sound-speed profiles for winter and summer.

therefore only approximate mean values with considerable uncertainty associated with them. The last two columns list the attenuation coefficients (dB/wavelength), which again are approximate mean values. Despite the uncertainty associated with the numbers given in Table I, we feel that these values are sufficiently representative of real ocean bottoms for us to be able to make a meaningful study of bottom effects on optimum frequency.

Next we selected two typical shallow-water sound-speed profiles (summer and winter), as shown in Fig. 4. Beyond a depth of 100 m, both profiles have a constant gradient of 1.8 m/s per 100 m. We then used normal-mode theory[15] to calculate optimum frequency versus water depth for the bottom types of Table I, introducing the following simplifications: (1) source always at mid-depth, (2) propagation loss averaged over the water column, (3) 80-dB contour line to be used as reference level. The first two simplifications were introduced to eliminate the dependence of the optimum frequency on source–receiver configuration, which, of course, is an additional complication to this problem. Generally, the optimum frequency increases when either source or receiver moves away from the mid-depth position. Also the optimum frequency is slightly dependent on the choice of reference level (80-dB line).

The results of the normal-mode computations are given in Fig. 5, where the optimum frequency has been contoured versus water depth and bottom speed. The winter results in Fig. 5(a) show little dependence on bottom speed (horizontal contour lines) while the optimum frequency changes drastically with water depth. Figure 5(b) displays a similar behavior for the summer with a particular profile effect showing up in the lower left corner of the graph.

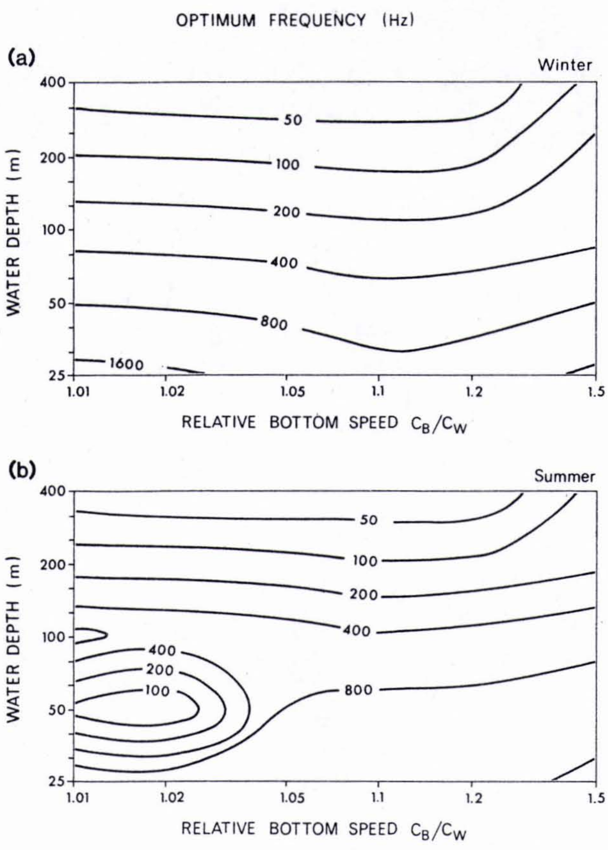

FIG. 5. Contoured optimum frequency versus water depth and bottom speed. (a) Winter; (b) Summer.

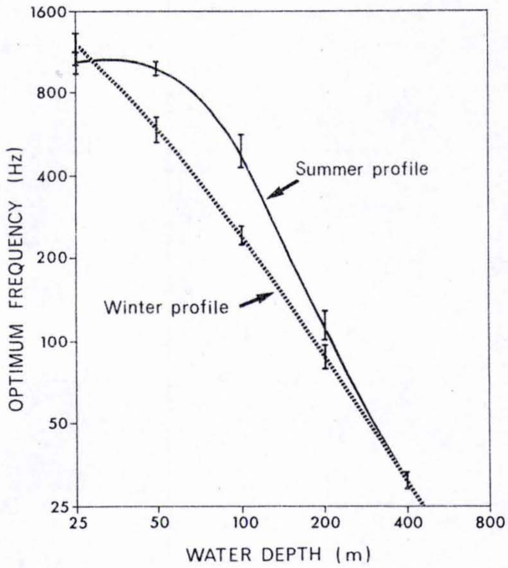

FIG. 6. Optimum frequency versus water depth for summer and winter profiles.

Anticipating the fact that all of the experimental data presented in this paper were taken over homogeneous bottoms with relative speeds between 1.02 and 1.20, we can concentrate on this range of bottom speeds and plot the average optimum frequency versus water depth for summer and winter, as shown in Fig. 6. The vertical bars on both curves indicate the variability with bottom type. The important result here is that even though bottom type changes significantly, the effect of water depth is dominant and suggests that mechanisms other than the effect of water depth can be studied in detail by scaling out water depth trends.

The calculations displayed in Fig. 6 show that the optimum frequency decreases with increasing water depth. This is due to the fact that, at a given frequency, there is decreasing bottom interaction with increasing water depth. Consequently, the bottom-loss mechanisms responsible for the existence of the optimum frequency will be dominant at still lower frequencies as water depth increases. We also see that the summer and winter results converge for increasing water depth, which is to be expected since seasonal changes associated with surface heating should become less significant as the overall depth of the water column becomes greater. On the other hand, we see that the summer and winter results also approach each other at a depth of 25 m; this is because both profiles used are isovelocity to this depth. It is interesting to notice in Fig. 6 that the optimum frequency for summer can be obtained from the winter curve by simply decreasing the water depth by the thickness of the heated surface layer (about 40 m). Therefore, under the above-mentioned simplifications concerning source and receiver positions, the optimum frequency of propagation for summer is equivalent to that for winter propagation at a reduced water depth. This analogy, of course, breaks down for small water

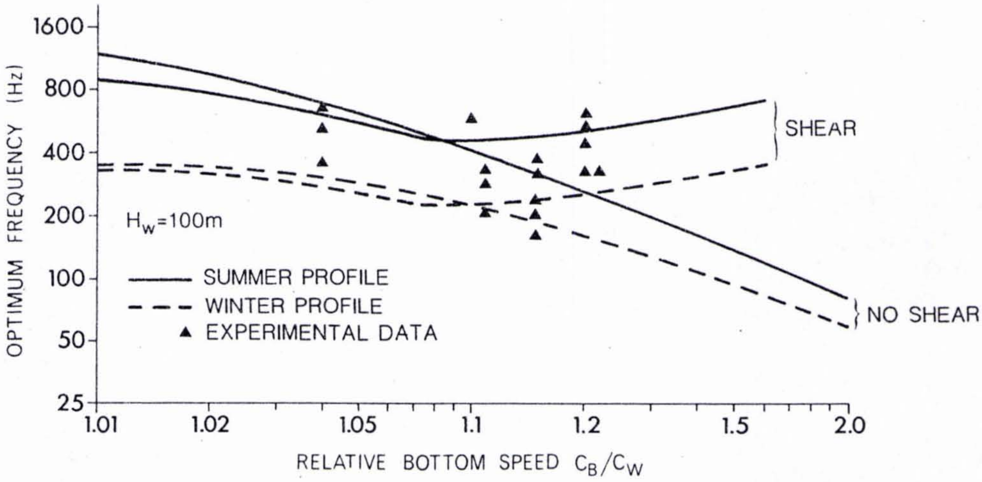


FIG. 7. Optimum frequency versus relative bottom speed for a water depth of 100 m. The experimental data are compared with normal-mode theory computations.

depths ( < 100 m), when the thermocline region dominates the summer profile.

We then proceeded to select broadband shallow-water data to check the theoretical computations. A literature search gave only a single data point,[22] which was because we had put the following constraints on the data: (1) sufficiently broadband to reveal the optimum frequency, (2) homogeneous bottom with appropriate geoacoustic information, (3) source at mid-depth and field averaged over depth or, alternatively, receiver also at mid-depth, (4) data presented in such a form that the 80-dB level could be used for determining the optimum frequency. Fortunately, a considerable amount of shallow-water data taken by SACLANTCEN could be used. These data comprise propagation runs done in different areas of the Mediterranean Sea and of the eastern North Atlantic in flat bottom areas with water depths ranging from 60 to 300 m.

All data points[10,22,23] were then normalized to a depth of 100 m using the curves in Fig. 6. The result is shown in Fig. 7 as optimum frequency versus relative (compressional) bottom speed, where the bottom speeds were obtained from core measurements. Also shown in Fig. 7 are the normal-mode results for the two seasons and the bottom types listed in Table I, again for a water depth of 100 m, a source depth of 50 m, and the field averaged over depth. Since the experimental data were also collected in intermediate seasons, we should expect data points to fall in between the theoretical curves for summer and winter. We see from Fig. 7 that the agreement between theory and experiment is good, particularly when shear waves in the bottom are included.

If the effect of shear is neglected, the optimum frequency is expected to decrease as the bottom speed increases. That is, sound does not penetrate as deeply in faster ocean sediments and, in addition, the lower the frequency, the lower the compressional attenuation of the sediment. However, we do not see this falloff in the optimum frequency when the effect of shear is included. The reason for this is that hard, high-compressional-speed sediments also have high shear speeds (see Table I) and though there is less acoustic penetration of the harder sediments, there is the generation of shear waves at the bottom interface that radiate into the bottom. Hence, this coupling into shear waves appears as an additional loss mechanism for sound in the water column. To sum up, our limited number of data points appear to be in agreement with the theory that includes shear wave effects in the bottom. Figure 7 also shows that the optimum frequency (not the actual field level at the optimum frequency) does not change much once the water-depth effect has been removed.

To complete this study we wish to address one last point. We mentioned that propagation levels, unlike the optimum frequency, are highly dependent on bottom type. This can be shown explicitly by defining an "optimum

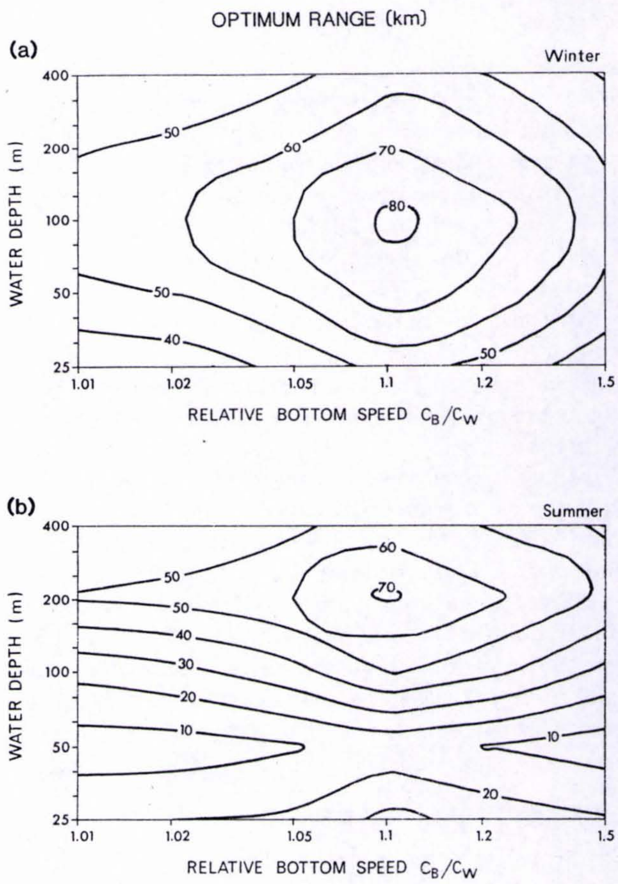


FIG. 8. Contoured "optimum range" versus water depth and bottom speed. (a) Winter; (b) Summer.

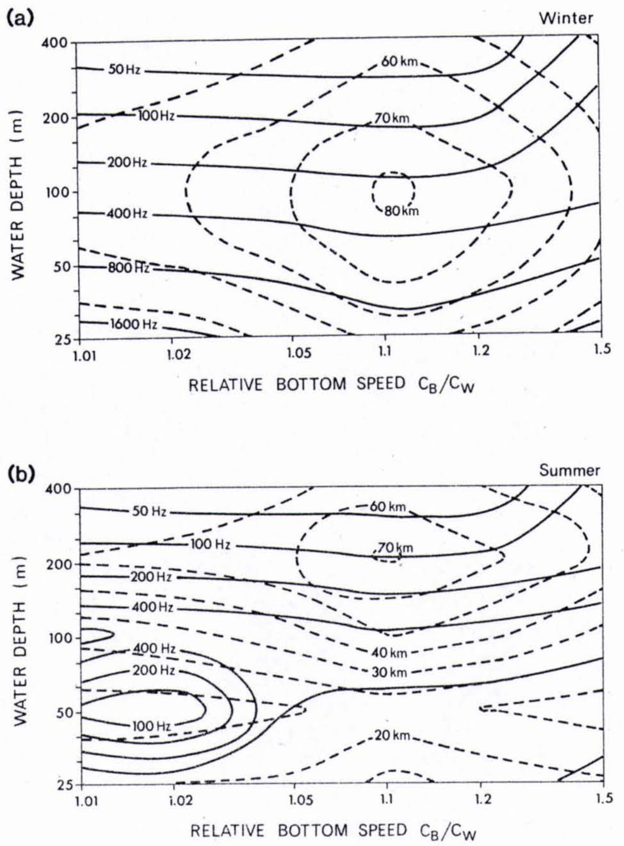


FIG. 9. Optimum frequency (full lines) and "optimum range" (dashed lines) versus water depth and bottom speed. (a) Winter; (b) Summer.

range" as that range in a specific environment where the optimum frequency has a level of 80 dB. We can then contour optimum range versus water depth and bottom speed. This is shown for winter and summer in Fig. 8. We see that in winter, for example, there is an optimum frequency of propagation in a water column of 100 m and a relative bottom speed of 1.1 such that there is an optimum range of 80 km (excellent propagation for coastal waters). For this same area we see that in summer the best optimum range occurs at twice the water depth, and that this optimum range is less than the winter value. This is consistent with our knowledge that losses are greater in summer due to increased interaction with the bottom.

Finally, if we combine Fig. 5 with Fig. 8 we end up with a kind of nomogram which gives us optimum frequency and optimum range versus bottom type and water depth, as shown in Fig. 9. Thus, for example, in the winter case discussed above, sound propagating at a frequency (which is optimal) of 200–300 Hz will have an optimum range of 80 km in a water depth of 100–150 m over a bottom with a speed of about 1.1 times the water speed. Any change in these parameters (frequency, water depth, bottom speed) from the optimal conditions invariably results in poorer propagation.

## III. SUMMARY AND CONCLUSIONS

In this paper we have presented data and theory that demonstrate that the optimum frequency of propagation is dependent on water depth, bottom type and season (sound-speed profile). We have shown that it is possible to scale out water depth in order to isolate the effects of the bottom on propagation. The limited amount of data available to compare with theory then indicated that the shear properties of marine sediments are an important factor in determining the optimum frequency of propagation. It is also clear from Fig. 7 that a conclusive experiment to determine the quantitative effect of shear on the optimum frequency of propagation would be performed over a very hard bottom with a relative bottom speed, $C_b/C_w$, of about 1.4 or larger.

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