GEO-ACOUSTIC MODELS FOR PROPAGATION MODELLING IN SHALLOW WATER[*]

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ABSTRACT

Acoustic propagation in shallow water is viewed as a guided-wave phenomenon, with the sea surface and seabed forming the boundaries. At sub-kilohertz frequencies, the acoustic properties of the seabed to a depth of several wavelengths can have a strong effect on propagation. The computer modelling of propagation requires estimates of such parameters as sound speed, density, attenuation, and layer thicknesses, which are collectively called the geo-acoustic model of the seabed. Direct measurement of these quantities is difficult, and methods must be devised to infer these values from other experiments, often employing acoustic techniques. At DREA, we have adopted the approach of independently determining as many geo-acoustic parameters as possible, and adjusting the less precisely known parameters within reasonable limits to effect an agreement between theory and experiment. To this end, we have used sub-bottom vertical reflection profiles to determine sediment types and thicknesses, large and small scale seismic refraction experiments to estimate sound speeds, and processing of sub-bottom reflection data to estimate volume attenuation. Examples of geo-acoustic models and comparisons with experiment are presented for shallow water sites on the Scotian Shelf and the southwestern approaches to the English Channel.

RESUME

La propagation des sons en eau peu profonde est considérée comme un phénomène d'onde guidée, la surface de la mer et le fond marin constituant les limites. Aux fréquences inférieures au kilohertz, les propriétés acoustiques du fond marin jusqu'à une profondeur de plusieurs longueurs d'ondes peuvent avoir une grande influence sur la propagation. La modélisation par ordinateur de la propagation nécessite l'estimation de paramètres comme la vitesse du son, la densité, l'atténuation et l'épaisseur des couches, qui portent collectivement le nom de modèle géo-acoustique du fond marin. La mesure directe de ces paramètres est difficile et on doit mettre au point des méthodes permettant de déduire ces valeurs d'autres expériences souvent basées sur l'application de techniques acoustiques. Au CRDA nous avons adopté une méthode visant à déterminer séparément le plus grand nombre possible de ces valeurs avant d'ajuster les valeurs des paramètres moins bien connus à l'intérieur de limites raisonnables pour faire correspondre les résultats expérimentaux à la théorie. A cette fin nous avons utilisé des profils de réflection sous le fond pour déterminer les types de sédiments et leur épaisseur, des expériences de sismique réfraction à petite et à grande échelle afin d'estimer les vitesses du son et le traitement des données de réflection sous le fond afin d'estimer l'atténuation de l'intensité. Des exemples de modèles géo-acoustiques et des comparaisons avec les résultats expérimentaux sont présentés pour des emplacements en eau peu profonde de la plateforme néo-écossaise et des approches sud-ouest de la Manche.

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1 Introduction

One component of DREA's research program in shallow water acoustics during the last several years has been the attempt to model acoustic propagation in a variety of shallow water environments. This effort, coupled with our bank of experimental data, allows us to study the influence of different environmental factors on propagation. This paper will describe the formation of geo-acoustic models of the seabed, concentrating on conditions in which the propagation is bottom-dominated.

The seabed properties of primary interest for the computer modelling of acoustic propagation are the sound speed, density, attenuation, and layer thickness. This paper will discuss various methods used to measure these properties; for example, sub-bottom profiling, seismic refraction, and dispersion analysis. Examples of geo-acoustic models and comparison of predictions with experimental propagation loss data will be presented for shallow water sites on the Scotian Shelf and the southwestern approaches to the English Channel.

The acoustic propagation of a given environment, source/receiver geometry, and frequency is often characterized by a quantity known as propagation loss (or transmission loss). This is defined to be ten times the logarithm (base ten) of the ratio of the acoustic pressure at the receiver to the pressure at a reference distance (1 meter) from an ideal point source. The units are then dB re 1 m. A spherical wave radiating from a point source exhibits a 20 log R range dependence, where R is the source/receiver distance. Acoustic energy propagating in a waveguide formed by two perfectly reflecting, plane-parallel boundaries exhibits a 10 log R dependence.

In a typical ocean environment, propagation loss has several contributing factors apart from geometric spreading, such as refraction by a depth-dependent sound speed, sea-water absorption, loss due to imperfect reflection at the seabed, and scattering of energy at rough interfaces and inhomogeneities. Imperfect reflection at the seabed may be due to absorption in the surficial sediment layers and/or conversion of compressional waves to shear waves at the interface. The role of the propagation model is to estimate the combination of all these factors, based on physical mechanisms and our best knowledge of the acoustic environment.

In Figure 1, the shallow water areas of primary interest to DREA are represented by the region inside the 500 m contour tracing the edge of the continental shelf. As well as containing a significant part of the trans-Atlantic shipping lanes, these areas undergo intense exploration activity for the possible exploitation of mineral resources, and host the fishing fleets of several nations. The seabed formations of these areas range from exposed bedrock and glacial till to sediment deposits of gravel, sand, silt and mud. The water depth on the shelf can be as shallow as 70 m on the bank areas, or as deep as 250 m in the basins.

Acoustic data from the Scotian Shelf and Grand Banks serve to demonstrate the range of propagation conditions that the acoustic modeler must be prepared to encounter in shallow water environments. In Figure 2, the curves of propagation loss vs range for a 1/3 octave band of energy centered at 40 Hz show a tremendous difference: the Scotian Shelf data show the same loss as would be predicted by a cylindrical spreading law, implying little bottom loss. In contrast, the Grand Banks data show considerably more loss than would be predicted even by a spherical spreading law, leading us to the conclusion that loss due to seabed interaction plays a significant role in this case.

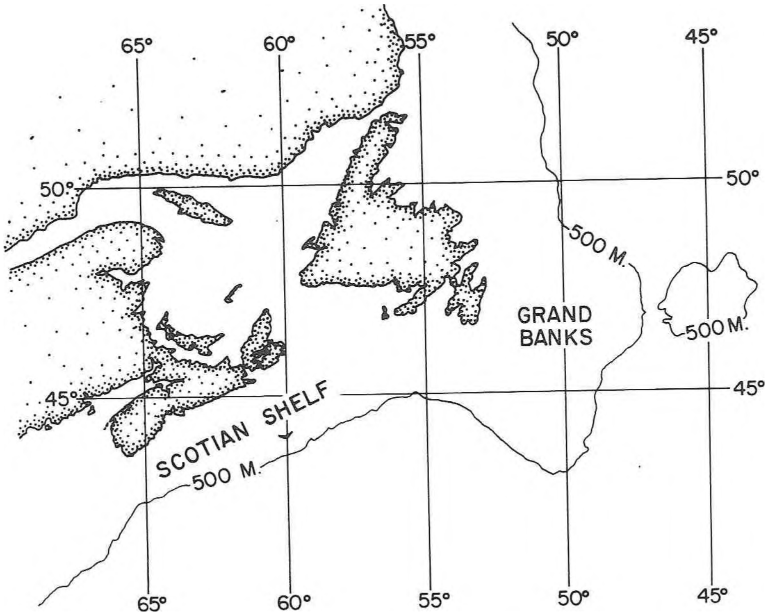

Figure 1. **The shallow water areas of primary interest to DREA, inside the 500 m contour.**

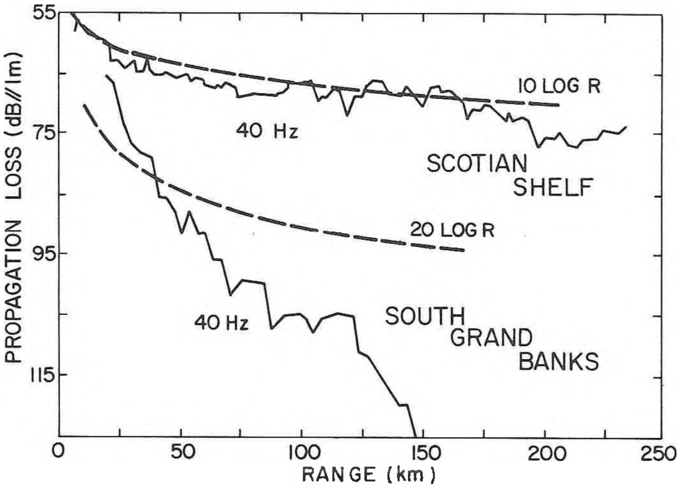

Figure 2. **Extremes of propagation variability.**

2 Modelling acoustic propagation in the ocean

As shown in Figure 3, the shallow water acoustics problem consists of solving the wave equation in the ocean waveguide bounded on top by the ocean surface, and on the bottom by the imperfectly reflecting seabed. These boundaries may be rough, and the medium is generally inhomogeneous, due to a depth-dependent sound speed profile. The variation of the waveguide properties in depth is typically much stronger than the variation in range, making this problem well-suited for analysis by a normal mode computer code using an adiabatic assumption [1],[2]. This assumption requires that no energy be transferred between modes propagating through a range-dependent environment. Mode coupling techniques [3], which transfer energy between modes, can be introduced to manage extreme range-dependence. Other models which can be used in shallow water are the parabolic equation (PE) [4], the fast field program (FFP) [5], and ray trace models [6], although each has its limitations.

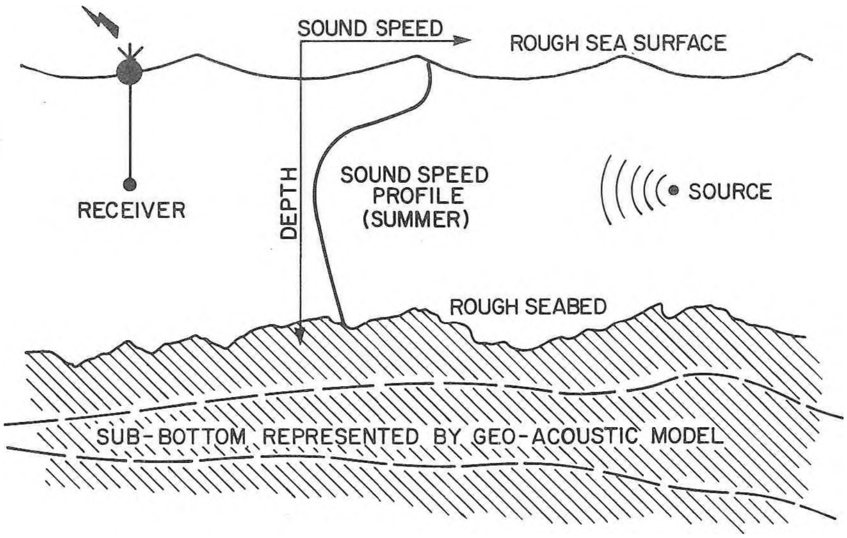

Figure 3. **The shallow water acoustics problem.**

It is the interaction with the seabed which provides the greatest challenge in the modelling of shallow water propagation, since the parameters needed for the geo-acoustic model are not generally accessible for direct measurement. Special experiments must be designed to extract the characteristics of interest. The construction of a geo-acoustic model of the seabed is a complex task, often iterative, and requires the compilation of facts from diverse sources.

The geo-acoustic model is generated in the form of a sequence of layers of sediment or rock having constant values of compressional wave sound speed, specific gravity, bulk attenuation, and shear wave speed. Vertical gradients of these values within a layer may be accommodated by sub-dividing the layer into finer piece-wise constant layers, although some normal mode codes can handle piece-wise linear variation of these parameters. Of those normal mode models which incorporate shear wave effects, most allow only the bottom-most layer to support shear, but there are specialised programs which treat the general problem. The present normal mode program at DREA uses a piece-wise constant geo-acoustic model, with no shear waves.

3 Sources for the model inputs

Oceanographic inputs for the propagation model are readily available: sound speed profiles in the water can be measured using expendable bathythermographs or conductivity-temperature-depth probes. The water depth can be measured using the source ship's echo sounder, or from a sub-bottom seismic profile survey. Surface roughness can be estimated visually, deduced from wind speed, or measured using devices deployed from the ship. In the absence of direct measurement of these factors, environmental data banks can provide an estimate of their expected characteristics.

Seabed characteristics are inferred from several sources: the main instrument used by DREA is a high-resolution vertical incidence reflection profiler [7] supplied by Huntec ('70) Ltd. This device generates a graphic record of the sub-bottom echoes from a broad-band source towed along the survey track, resolving features as small as 1 meter, and penetrating the surficial sediments to a depth of several tens of meters, depending on the bottom hardness. Seismic refraction and wide-angle reflection experiments provide estimates of the layer velocities and thicknesses. Dispersion analysis of transient arrivals provides group velocity values which can be compared with modelled values. For some areas [8], the seabed types have been compiled into reference charts which can be consulted in the absence of direct measurements to provide a crude geo-acoustic model. The published literature on the geophysical characteristics is always consulted to take advantage of previous surveys, and to guide the interpretation of the newly acquired data.

3.1 Seismic profiling

Figure 4 is a reproduction of the graphic output of the Huntec seismic sub-bottom profiler, taken from a region on the Scotian Shelf exhibiting different seabed formations. A geo-physicist has interpreted this record with the aid of "ground truth" obtained from more traditional survey techniques such as core sampling and grab sampling. In addition to the echo time series, the analysis software provided with the system estimates the percentage of energy reflected [9] at the water/sediment interface, r_1, and the percentage of energy scattered non-specularly, r_2. As the outcropping sediment laterally grades from glaciomarine sediment to holocene clay, notice that both of these values decrease and that the fluctuation in r_2 is greatly reduced. These reflectivity values aid in the identification of the surficial sediment, especially when there are no distinctive features such as the bedding in the sediment. Note here, and in many of the figures which follow, that the horizontal scale is several orders of magnitude greater than the vertical scale.

Another method of processing applied to these data generates a time-frequency plot [10], or sonogram, of the received energy. The frequency dependence of the energy from the seafloor return is compared with that from a buried coherent reflector. Assuming that the attenuation coefficient (the loss in dB/m suffered by a plane wave) varies linearly with frequency, an average value for the layer can be estimated. Typically, this value varies from place to place and with layer thickness, but the values obtained are useful in placing bounds on the parameters of the geo-acoustic model.

Figure 5 shows an interpreted profile for use in the geo-acoustic model for an area in the southwestern approaches to the English Channel (SWAP). The sediments have been classified by geological period, after consulting the geo-physical literature [11]. The Pliocene to Recent sediments are unconsolidated, and vary considerably in thickness due to the occurrence of sand bars. The Paleogene layer is a more compacted material, and the Upper Cretaceous layer is a semi-consolidated bedrock, probably chalk. The sound speeds have been assigned according to the literature, and the attenuation values were measured at points where the various sediment types outcrop at the sea floor. The large variation in the sand values may be due in part to a depth dependence of attenuation, since it has been proposed that there is a negative gradient of attenuation in unconsolidated sediments [12].

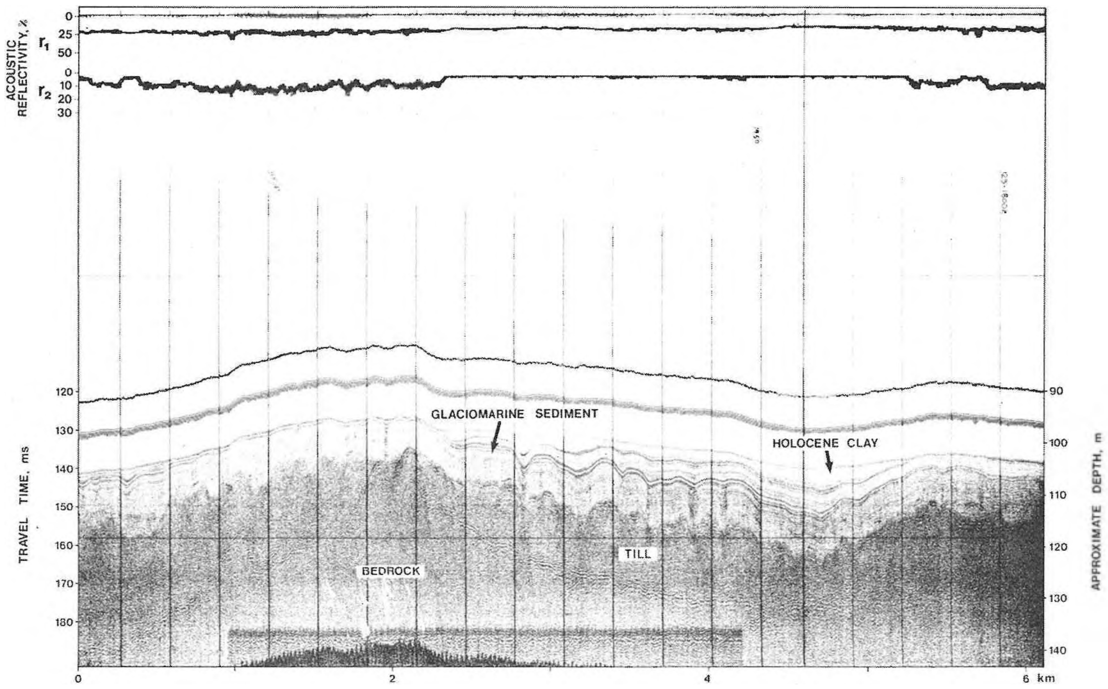

Figure 4. Graphic output of the Huntec ('70) Ltd. seismic profiler.

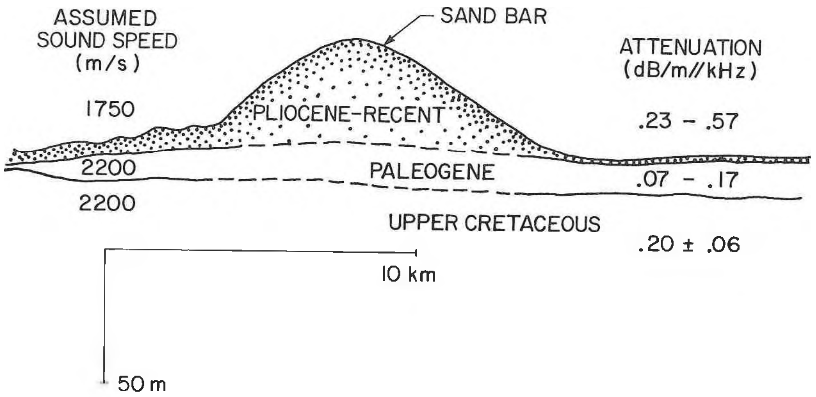

Figure 5. Geological interpretation of the seismic profile for an area in the southwest approaches to the English Channel.

3.2 Seismic refraction

Seismic refraction, illustrated in Figure 6, makes use of energy critically refracted along a layer boundary, giving a linear relationship between range and travel time. Arrivals at a horizontal array of sensors can be processed to give the velocities of several consecutive layers, and their thicknesses. Geophysicists use this technique on a scale of tens or hundreds of kilometers to investigate the layering of the earth's crust to a depth of several kilometers. The Geological Survey of Canada have an array of considerably smaller size which is used to investigate the permafrost layer at the bottom of Arctic waters [13]. Data from this same array deployed on the Scotian Shelf have enabled us to measure velocities within the surficial sediment layers, and to measure layer thicknesses. A similar device is being developed for the measurement of shear wave velocities.

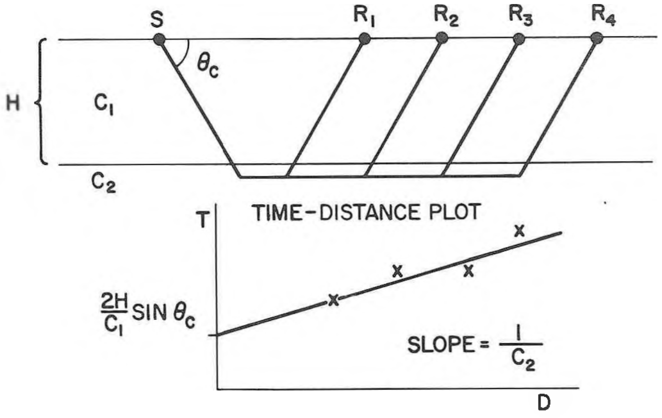

Figure 6. **Schematic representation of the seismic refraction measurement process.**

3.3 Dispersion analysis

The dispersive nature of the shallow water waveguide [14] causes time spreading of the various frequency components of a transient signal as it propagates downrange. Figure 7 shows a time series from an explosive deployed in a region near St. George's channel between Cornwall and Ireland, where the surficial sediment layer is quite thin, and Cretaceous bedrock forms the seafloor. The first arrival is a low-frequency signal due to refraction of the compressional wave at a high-speed bottom layer. The earliest high-frequency energy travels at the minimum phase velocity in the water column. The Airy phase is the arrival corresponding to the group velocity minimum of a given mode, in this case probably mode one. The Scholte wave is an interface wave travelling at just less than the shear speed in the bottom [15]. For non-crystalline bedrock, this is usually slower than the minimum phase velocity, so the interface wave is the last arrival. A quantitative analysis of transient arrivals can give curves of group velocity vs frequency which can be compared with theoretical curves calculated using the geo-acoustic model. In this way, the layer velocities and thicknesses of the geo-acoustic model can be tuned. We have not yet pursued this line of investigation at DREA, although other workers have employed this technique with success [16].

4 Comparison of model and experiment

With a combination of the above methods, it should be possible to generate a reasonable geo-acoustic model for an experimental site. We have done this for several areas on the Scotian Shelf and the southwest approaches to the English Channel.

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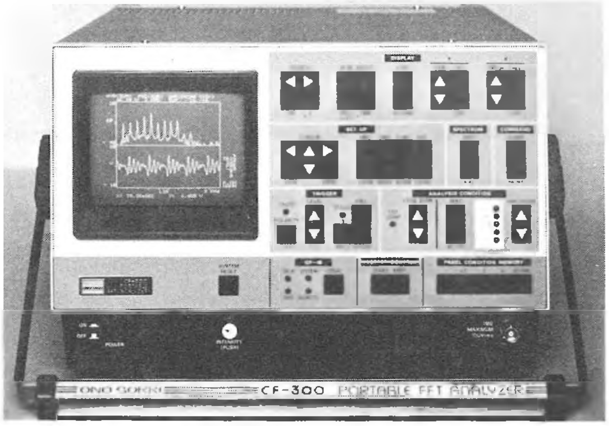

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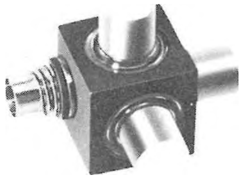

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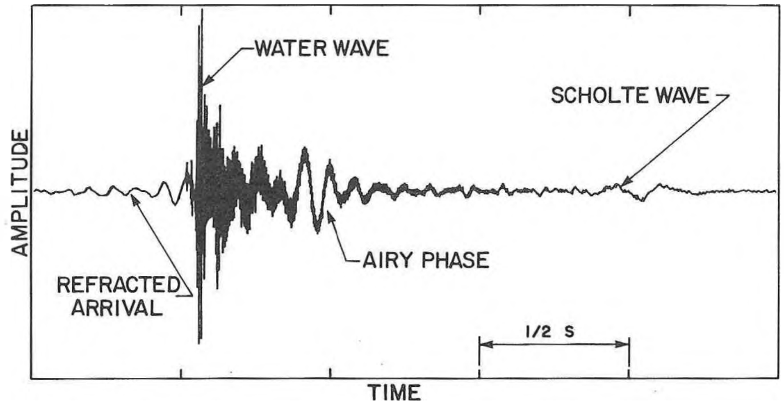

Figure 7. Time series of an arrival from an explosive source, showing the principal features of dispersion.

4.1 Scotian Shelf

Figure 8 shows the bathymetry and sound speed profiles for a propagation run over a track on the Scotian Shelf, in winter. The sound speed profile is slightly upward refracting, but the shallow depth ensures a large contribution to the propagation loss from seabed interaction.

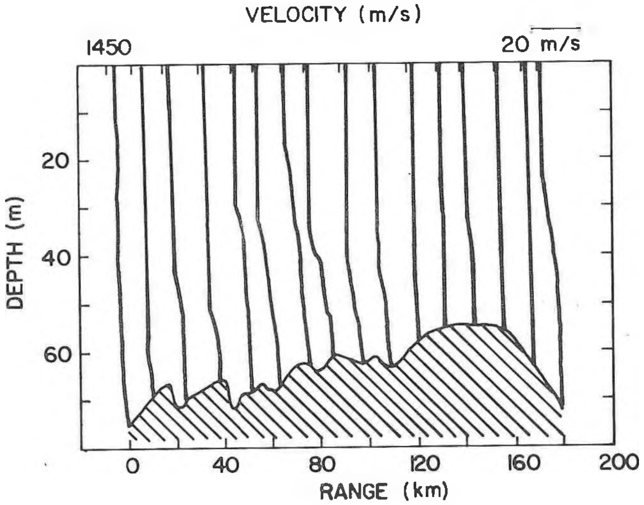

Figure 8. Bathymetry and sound speed profiles for a propagation track on the Scotian Shelf, in winter.

Figure 9 shows the range-dependent, segmented geo-acoustic model for this run. We have previously published the parameters of the geo-acoustic model, as well as the results shown here [17],[18]. The geo-acoustic parameters are contained in Table 1. The piece-wise constant layering is based on Huntec profiler records, and the sound speeds have been assigned by seismic refraction experiments. The attenuation in the sand was based on sonogram analysis [10], which in general gives estimates that are lower than those of Hamilton [19].

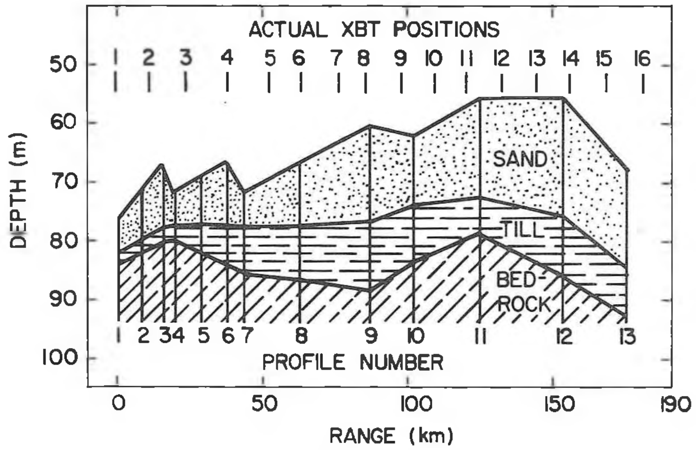

Figure 9. The geo-acoustic model for the Scotian Shelf track.

Table 1

Acoustic Properties of Sediments - Scotian Shelf

Type	**Sound Speed** (m/s)	**Density** (g/cm^3)	**Attenuation** (dB/m//kHz)
Sand	1750	2.1	0.26
Till	1900	2.1	0.08
Bedrock	2050	2.2	0.05

The experimental data (heavy lines) and model predictions (light lines) for a urce and receiver approximately at mid-depth are shown in Figure 10 for the three west frequencies. The experimental data are 1/3-octave averages, but still show nsiderable fluctuation. The model results are narrow-band, but interference fects have been removed by summing over the modes incoherently. We feel that the reement is reasonable, except at 25 Hz. Rather than increase the loss by creasing attenuation in the sand or decreasing the sound speed, we have left room r shear wave effects to supply the extra loss required, when they are included in e propagation model.

At the intermediate frequencies of 200 Hz and 400 Hz, shown in Figure 11, the t of model and experiment is not as good. Since the fit was good for the lower equencies shown on the previous figure, we feel that the gross features of the o-acoustic model are correct, and that agreement at the intermediate frequencies y be obtained by honing the finer details of the model. We have tried including und speed and attenuation gradients in the sand layer. We also tried a non-linear equency dependence of attenuation in the sand. Neither of these refinements has proved the fit. The good fit at 800 Hz can be attributed to scattering at the a-surface, a common high-frequency loss mechanism in winter. Akal [20] has shown at losses above the optimum frequency of propagation are less dependent on bottom

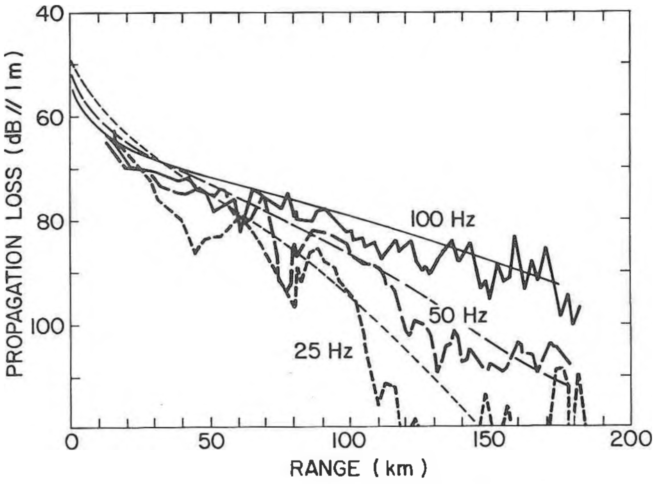

Figure 10. **Experimental propagation loss data and model results for the Scotian Shelf site, 25 Hz-100 Hz.**

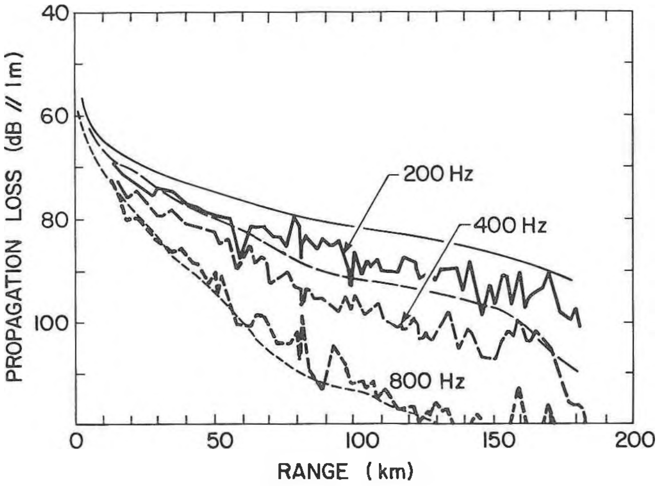

Figure 11. **Experimental propagation loss data and model results for the Scotian Shelf site, 200 Hz-800 Hz.**

effects than on high-frequency loss mechanisms such as scattering or seawater absorption. Since the optimum frequency in our case is about 150 Hz, the required improvement may result not from adjusting the geo-acoustic model, but from some loss mechanism not yet included in the propagation model.

4.2 **Southwestern approaches to the English Channel**

Figure 12 shows the bathymetry, sound speed profiles, and interpreted geological profile for a propagation track in the southwest approaches to the English Channel, in summer. The velocities and attenuations were assigned as discussed earlier. A range-dependent, segmented geo-acoustic model similar to the previous case was constructed for this environment.

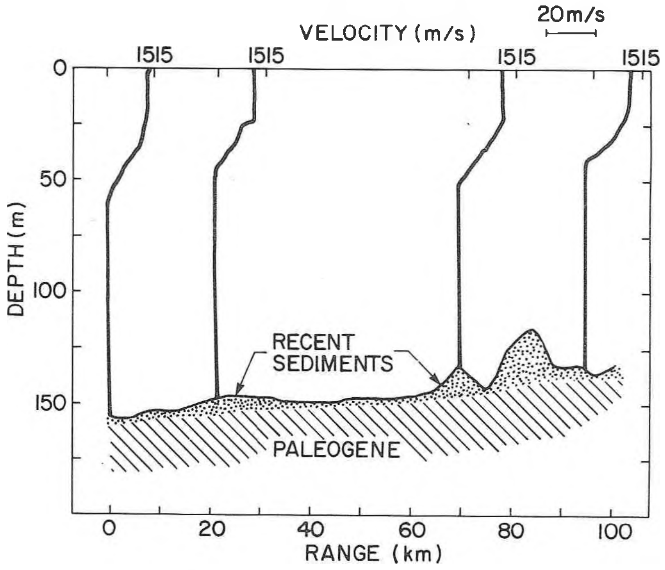

Figure 12. **Bathymetry, sound speed profiles, and interpreted geological profile for the southwest approaches to the English Channel.**

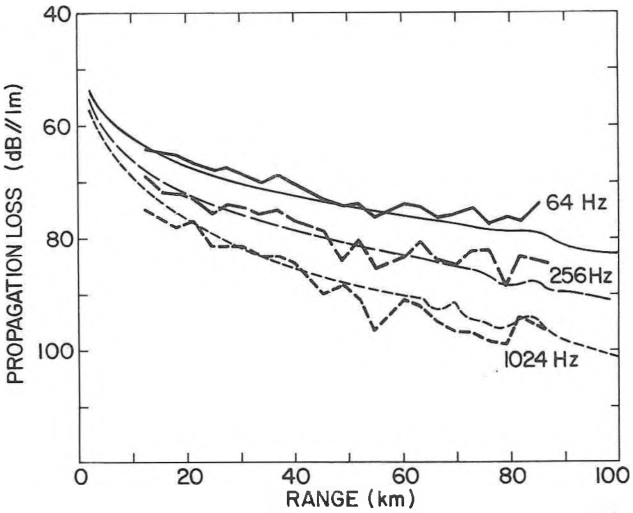

Figure 13. **Experimental propagation loss data and model results for the site in the preceding figure.**

Figure 13 shows the experimental data (heavy lines) and model results (light lines) for this case. The data in the range 25 Hz - 64 Hz are not shown since they were essentially the same as the 64 Hz data. The model reproduced this result. There is perhaps some disagreement at 1024 Hz, but this is probably not due to a fault in the geo-acoustic model. Surface scattering does not supply the required loss in this case, since the summer profile isolates the dominant modes from the surface. Note that agreement at low frequencies has been obtained without introducing shear wave effects. Although we have no measurements of the shear speed in the bottom, the modelling results suggest that it is low and of little consequence to propagation at the frequencies considered here.

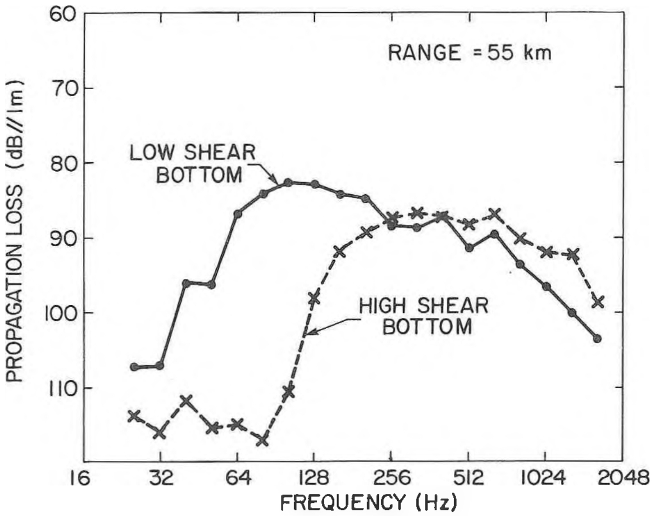

Figure 14. Data demonstrating the effect of a seabed supporting shear waves.

Although we have no shear wave capability in our propagation model, we do have some data which encourages us to include this effect in the future. The data shown in Figure 14, also from the southwest approaches to the English Channel, are from two tracks radiating from the same receiver position, at similar ranges, but over completely different seabed types. The curve showing the better propagation at low frequency corresponds to a seabed similar to that in Figure 12, having a low shear speed. The curve showing the higher losses at low frequency corresponds to a seabed composed of Cretaceous bedrock, which is likely to have a higher shear speed. We attribute the higher losses of this track to conversion of compressional waves to shear waves at the water/seabed interface. In this case there is no "insulating" layer of unconsolidated sediment over the bedrock, as we have seen in previous examples.

5 Conclusion

In conclusion, we have shown the sources of information we use to construct geo-acoustic models of the seabed, and the results of our attempts to model shallow water propagation. The results have shown moderate success, in that some environments are acceptably modelled using a simple geo-acoustic model. Other environments provide data for which agreement over a wide frequency range is difficult to obtain. A schematic view of the modelling process is shown in Figure 15. In some cases a more refined geo-acoustic model may provide the required improvement. For example, more investigation into the effect of sound speed and attenuation gradients is required, and the non-linear frequency dependence of attenuation should be considered further. In other cases, the propagation model itself may have to be improved by including an effect previously ignored. In our own modelling efforts, we have identified a need for improved high-frequency loss mechanisms in the model, and for the inclusion of shear wave effects. We have avoided the temptation to "fit" the curve by adjusting the several parameters at our disposal, unless we have justification from independent seabed studies. This philosophy does not always produce a satisfactory agreement between theory and experiment, but we have found that we often learn more about the problem when theory does not fit experiment, than when it does.

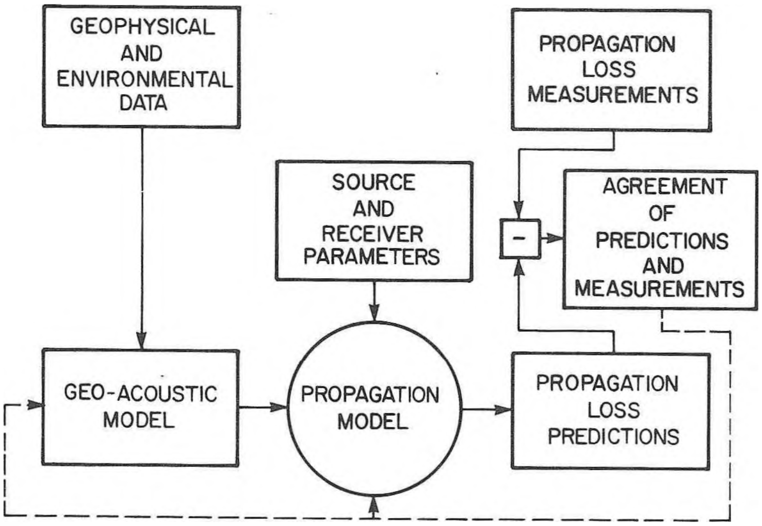

Figure 15. Schematic illustration of the modelling process.

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