Determination of Velocity Profile and Sea Bed Characteristics from High Frequency Pulse Propagation in a Shallow Water Mediterranean Environment

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Abstract

Time-domain features of shallow water Mediterranean and Yellow Sea data are simulated for frequency band widths of 0.8 kHz with a central frequency of 3.2 kHz. Contour plots of pulse arrivals in time and depth are analyzed for several source locations and receiver off-sets. Calculations have been carried out using a new Shallow Water Acoustical Modal Propagation model - SWAMP. Results indicate the ability to extract the adumbration of velocity profiles, critical angles of the ocean bottoms and source localization.

1. Introduction

The examination of the transmission loss in a wave guide over range and depth may reveal limited information about ducting and even less about ocean bottom properties. Researchers have become accustomed to examining transmission data and may be skilled with interpreting data to form reasonable guesses of desired properties. Data for the less studied pulse problem, particularly, for contour plots over depth either in range for fixed time or in time for fixed range appears more likely to reveal information of both the velocity profile and bottom properties. Indeed, a single array over depth for pulse signals would yield far more information than a sequence of arrays over depth distributed over a broad range in uniform steps required to produce single frequency contours. A single horizontal array for fixed frequency over range would likely yield ambiguous information, while in time-domain calculations it would yield relative arrival times of modes and thus possibly give a measure of ocean bottom properties. In the presence of ducting and poor placement, it could miss some modal arrivals and would unlikely give the information about ducting. Shallow water measurements yield less information about profiles, because they require larger frequency band widths to achieve comparable resolution in contrast with the deeper water cases and because mode stripping is more pronounced in range for the shallow water case and may lead to vague results in range as more and more modes are stripped particularly when the number of modes are small. What we wish to show here is how to exploit information from transmission loss or pressure fields from pulse signals in time steps for fixed range or in range steps for fixed time. The particular information we determine is at the very least an adumbration of the velocity profile as well as the critical angle of the bottom. We use the velocity profiles obtained from a shallow water Mediterranean region (80m) to explore strong features of pulse arrivals that are characterized by the velocity profile and bottom properties. The profiles typically have broad bottom ducts in about 80 meters of water commencing at about 30 meters. The gradient is not strong and varies over most of the bottom 50 meters of depth. There is surface ducting in some of the profiles which can be seasonally observed in the experimental measurements . We calculate arrivals at uniform depths over the entire range of the water column and plot outputs of arrivals in terms of group front intensity contours over time windows that encompass the entire pulse widths. The sources are alternatively placed in two locations, namely close to the surface and close to the bottom of the water column. The off-set distances are 2.5 km, 5 km and 7.5 km. The pulses vary from 2.8 kHz to 3.6 kHz, with a band width of 800 Hz and a central frequency of 3.2 kHz. The effect of surface ducting is of particular interest and is seen to have the effect of capturing energy from high angle modes that traverse from the bottom ducted region and are manifested as uniform discrete arrivals that have earlier arrival times than the predominate bottom ducted low mode group arrivals. The results indicate that some systematics are obtained that are useful in extraction of overall features of both the sound speed profile and the spectrum of angular modes governed by bottom properties. Further we show that source localization can be obtained by examining crossing patterns of the group intensity contours. A comparison of this result is made with Yellow Sea data which have much stronger gradients and lead to rather different group intensity arrival features. An interesting feature of strong bottom ducted profiles with some surface ducting was observed in an analysis of data from the Florida Straits by Harry DeFerrari and Charles L. Monjo. [1,2] For a 550 m water column and pronounced bottom ducting with weak surface ducting over the first 70 m of the water column, pulse signals are observed to get trapped periodically as high angle modes initiated at the bottom of the wave guide traversed to the top and returned to the bottom in a typically cyclical manner. However, at each contact of the higher order modes made with the upper surface duct some energy was trapped in that duct and traveled at the some what higher characteristic group velocity, thus leading to discrete localized arrivals that preceded the major and typical duct arrivals. This rather remarkable and unexpected results which may be initiated above some frequency threshold can give a powerful sensitive tomographycal tool that enables one to determine additional refined structures of a wave guide. In addition to giving evidence of surface ducting, it allows one to determine source distance and ocean depth. This observation is presently referred to as the DeFerrari-Monjo effect and we investigate it for the shallow water cases presented here.

2. Method of Calculation

The pulse propagation problem in oceanic waveguides can be solved via the frequency domain by Fourier synthesis of CW (continuous wave) results:

$$p(\mathbf{r},t)=\frac{1}{2\pi}\int_{freq.band} S(w)p(\mathbf{r},w)e^{-iwt}dw, \tag{1}$$

where $p(\mathbf{r},w)$ is a spatial transfer function, $S(w)$ is a source spectrum. Thus, the first computational step is associated with solving the Helmholtz equation with the source spectral function $f(\mathbf{r},w)$:

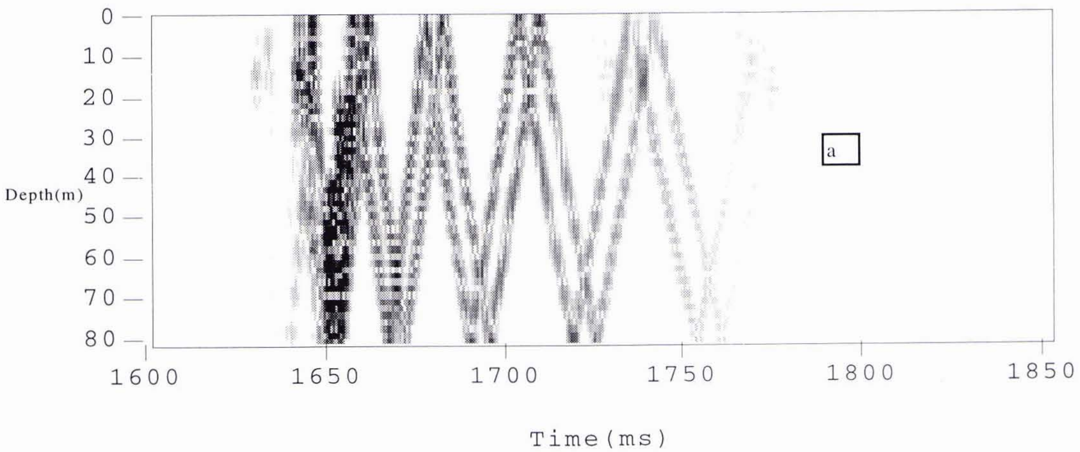
$$\left[\nabla^2+\frac{w^2}{c^2(\mathbf{r})}\right]p(\mathbf{r},w)=f(\mathbf{r},w) \tag{2}$$

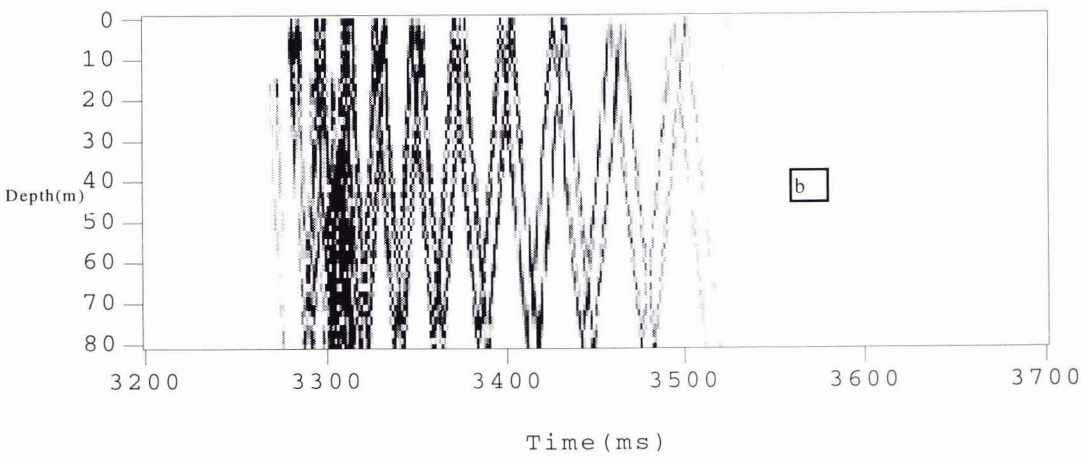
and generating the transfer function at a number of discrete frequencies within the frequency band of interest. The evaluation of the integral in (1) can then be done by, for instance, the Fast Fourier Transform at each spatial position ($\mathbf{r}$). Despite the relative simplicity of (1), there is no universal solution technique avalaible for arbitrary sound speed profiles $c(\mathbf{r})$.

The numerical results presented below were obtained by using a new normal mode model SWAMP. The variable velocity normal mode solution given by SWAMP is based on obtaining the solution of a related reference isovelocity problem. [3,4] Ocean bottom layering is assumed to be composed of fluid layers, but large numbers of layers are feasable so that it is possible to account for gradient effects. As in any normal mode model, it is not difficult to generalize to include layers with elastic properties. Once the depth dependent iso-velocity eigenfunctions are obtained, they are used as spanning functions that transform the isovelocity space solution by means of a rotational or unitary transformation into solutions of a space with a variable velocity profile. The transformation may be viewed as a worping operation that deforms the iso-velocity space into a variable velocity space. However, the spanning functions which are readily transformed into a spherical representation are retained, so that solutions of the distorted space may easily be expressed in a spherical representation, albeit a linear combination of such functions. This is an important development, because a spherical representation is required in the development of a unified approach that couples free three dimentional scattering solutions with a wave guide solution. The new modal eigenvalues are obtained by transforming the worping super matrix - which is real and symmetric - to tri-diagonal form from which the eigenvalues of the transformed space are readily obtained. Once the eigenvalues are obtained, sets of linear equations that form independent sub-systems are obtained. Each system of equations is in a linear solver form, represents independent systems and generates the required eigenfunctions in terms of expansion coefficients of the spanning space. Because the system of equations are independent, only one or any desired set of eigenfunctions may be obtained. Since the set of expansion matrices forms a super-matrix that is rotational by design, the new eigenfunctions are guaranteeded to be orthogonal as required by the nature of the problem. Since each of the solver equations are independent and are not based on iterative calculations which for example occurs in Gram-Schmidt construction, errors are not accumulated that often result in violation of the orthogonality conditions. The detailed consideration of the method is presented in the referenced literature. Here we would like to discuss what can be learned from the numeraical studies of the pulse propagation obtained by using SWAMP. It is important to notice that the model works reasonably fast for high-frequency calculations and successfully competes with the Parabolic Equation approach models with respect to computational time.

3. Numerical Simulation and Interpretation of the Results of Mediterranean Data

The first environment which was tested represents the typical shallow water Mediterranean waveguide with wide single bottom duct, described in the introduction. Figure 1 shows the intensity picture of the received pulse vs. depth vs. time for ranges (a) - 2.5, (b) - 5, (c) - 7.5 km. The source was placed in the duct, at depth 65 m.





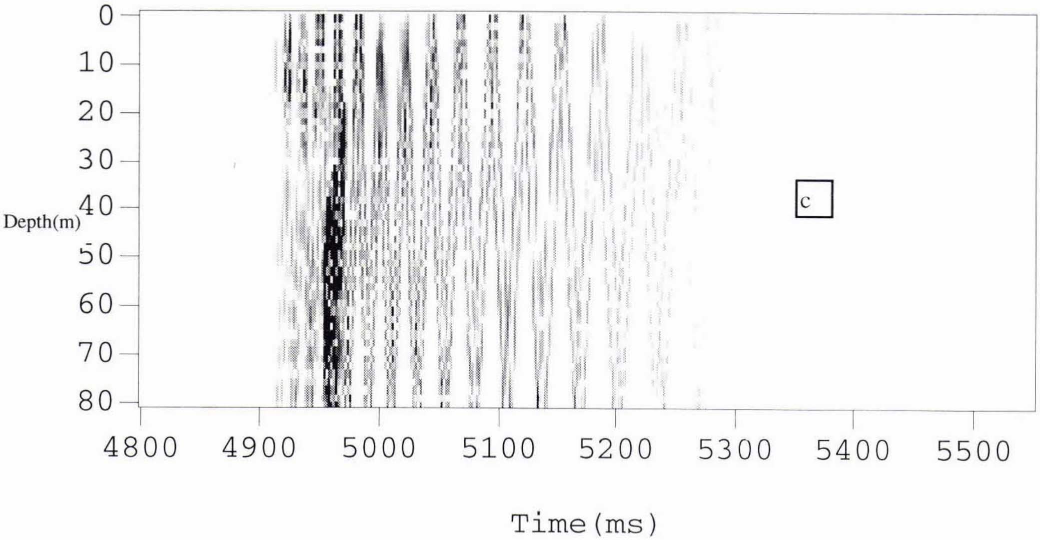
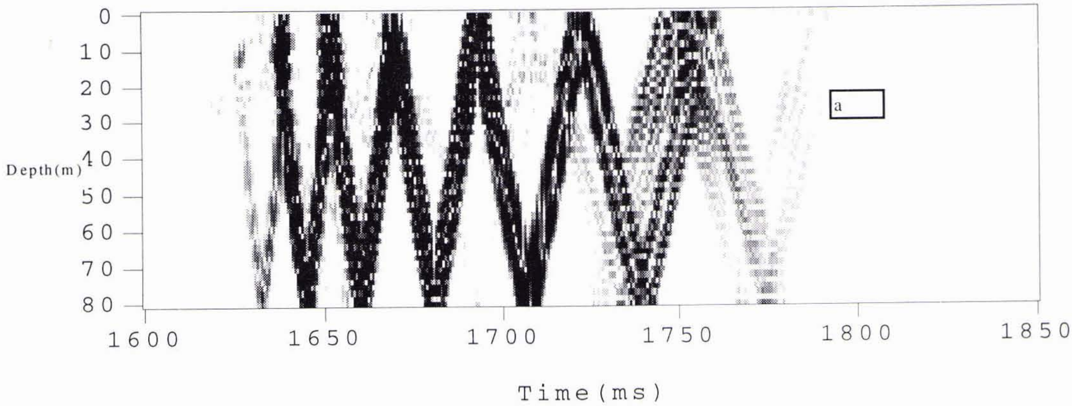


Figure 1. Arrived pulse structure for the single duct Mediterranean environment with the source at depth 65 m for distances: a - 2.5 km, b - 5 km, c - 7.5 km.

We can see that the low order modes are trapped in the duct and are the major first arrivals. The high order modes correspond to Surface-Reflected-Bottom-Reflected (SRBR) paths are well observed at the tail of the pulse. SRBR arrivals can be modeled as clustered groups of modes with different group velocities and with different modal angles with respect to horizontal or vertical axis. Thus, the travel time separation between these arrivals for fixed depth expands with increasing time. The intensity group fronts change as a function of mode angle with the vertical axes from 0 degree for the earliest major arrivals to the critical angle for the later "coda" waves determined by the total bottom impedance. The higher order modes can be approximated by the sum of up-going and down-going plane waves with the same inclination angle. The simple geometrical consideration shows that the intersection of intensity lines forms the source image at its real and imaged depths. It gives a simple geometrical algorithm to determine the source localization. If the source is located out of duct, the excitation coefficients for the low-order modes are small and we cannot effectively excite these modes. Thus, for this source geometry we may not obtain reliable information about the presence of the duct from any receiver geometry. This effect is manifested in Figure 2.

By introducing weak surface duct, we can observe that results does allow for some energy to arrive ahead of the main arrivals (precursors) due to approximate maxima values of the group velocity in the upper duct region. At that point the returns are not susceptible to arrivals interpreted in terms of the mathematical definition of "group" velocity since the second order asymptotics from the method of stationary phase fails and group velocity concepts are rendered meaningless. In that case the pulse amplitudes are frequency-modulated and lead to precursor waves. For some surface duct trapping the precursor effect is particularly pronounced and is particularly well discussed in the seminal work of Monjo and DeFerrari. [2] The DeFerrari-Monjo effect is present for the same Mediterranean duct with a slight surface duct added to it. This is evident in Figure 3 for the Mediterranean profile with a slight surface duct for which we are able to identify additional and more pronounced precursors. These precursors correspond to energy that is trapped in the upper duct region from the higher modes that traverse the wave guide from the bottom. It is conditional upon non-leaky trapped modes at the upper duct surface and accordingly there is a frequency cut-off below which no trapping will take place. Thus, it may be viewed as a high frequency feature.



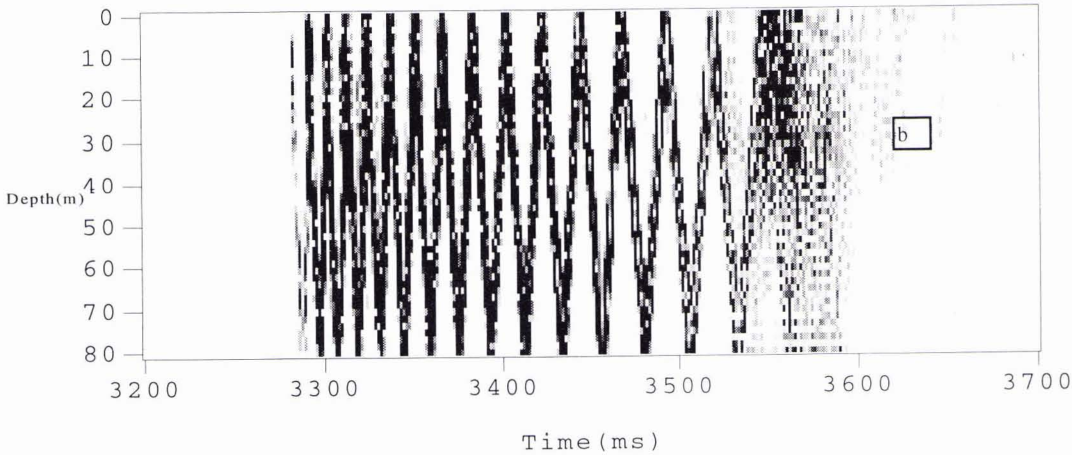
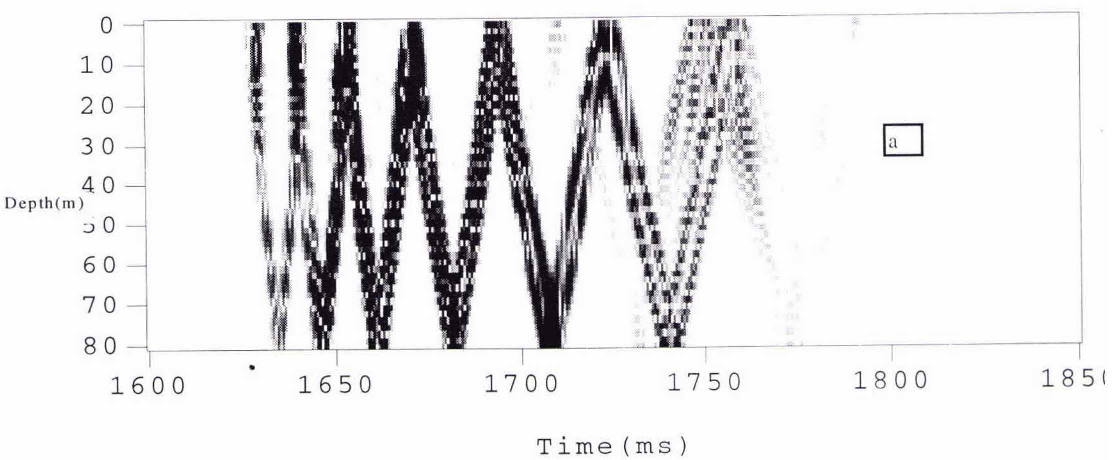


Figure 2. Arrived pulse structure for the single duct Mediterranean environment with the source at depth 10 m for distances: a - 2.5 km, b - 5 km.



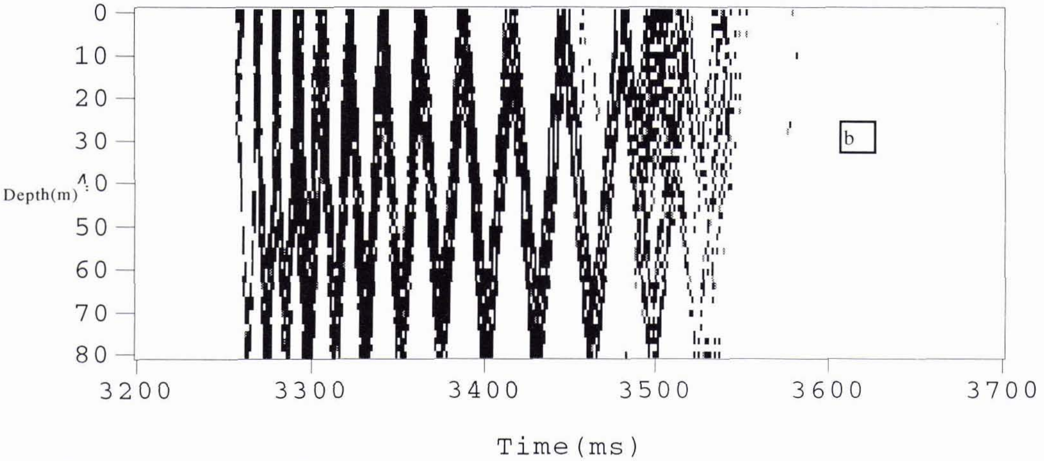


Figure 3. Arrived pulse structure for the added weak surface ducting duct Mediterranean environment with the source at depth 10 m for distances: a - 2.5 km, b - 5 km.

Since the Mediterranean profile is rather broad extending from 30-80 meters in a gradual fashion the outline or adumbration of the velocity profile though present is not strong. The next example of a similar region but with a narrower and stronger and more precipitous duct yields a "profile adumbration" that is much more pronounces.

4. Numerical Simulation and Interpretation of the Results of Yellow Sea Data

The Yellow Sea profile has a very much stronger gradient and progresses rapidly to the bottom of the water column. Thus, the effect of the profiles are more evident and one may observe a reasonable suggestion - adumbration of the velocity profile. In these calculations we have allowed for some small surface ducting for calculations represented by Figures 4-6, so that the arrivals of strong precursors leading the main bulk of arrivals is always present for these examples. However, in Figures 5 and 6, when the source is at the mid-point of the water column or in the main bottom duct we see a rather pronounced outline of the ducted region, so that for strong ducting in this case and other examples the outline of the ducting is to a reasonable degree associated with the actual velocity profile. Once again the critical angle of the bottom is determined by the "coda" arrivals which presents one with a means to extract the critical angle of the fluid-bottom interface and the relative sound speeds of the bottom.

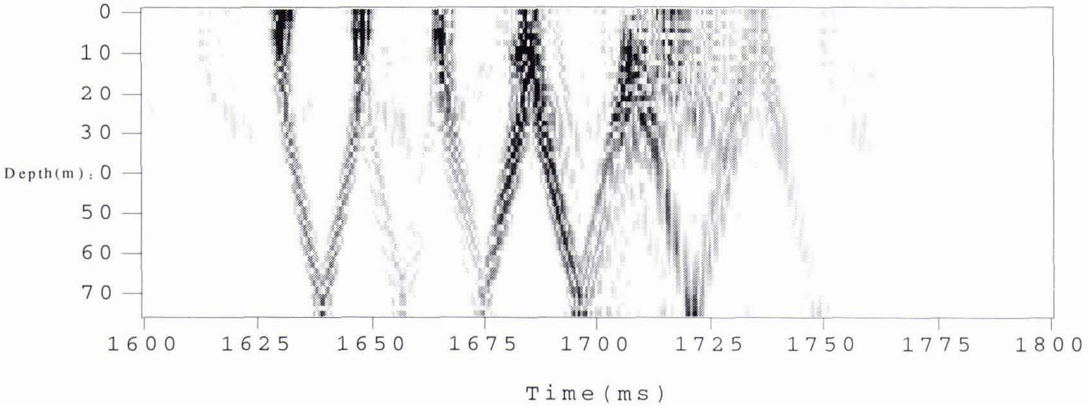


Figure 4. Arrived pulse structure for the Yellow Sea environment with the source at depth 7 m for distance 2.5 km.

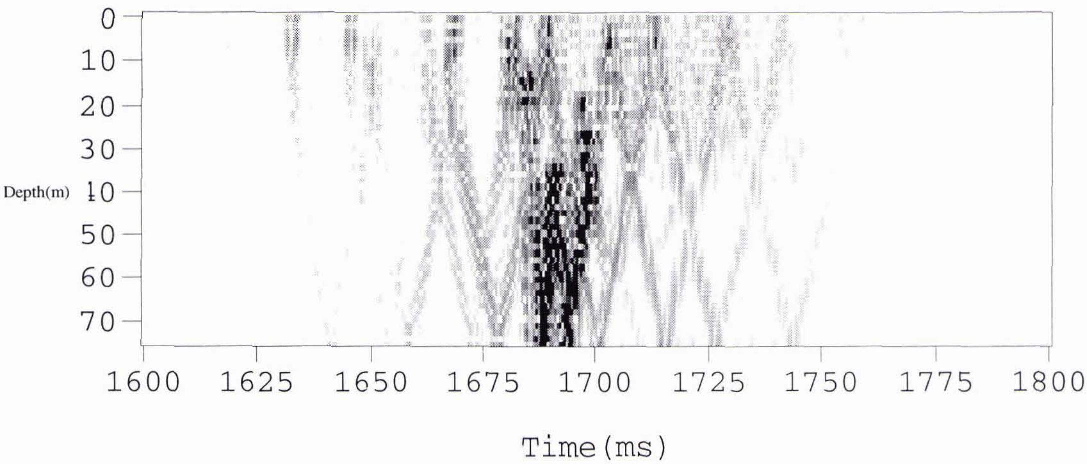


Figure 5. Arrived pulse structure for the double duct Yellow Sea environment with the source at depth 38 m for distance 2.5 km.

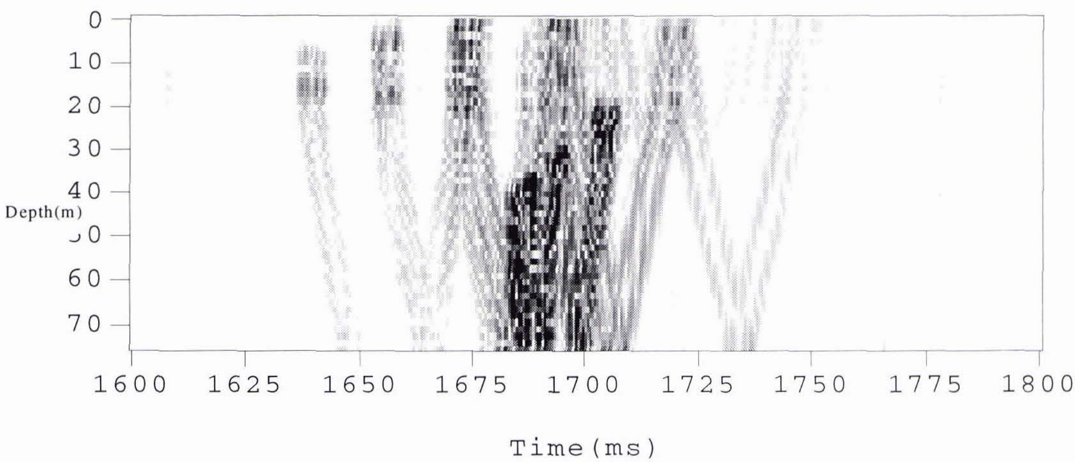


Figure 6. Arrived pulse structure for the double duct Yellow Sea environment with the source at depth 65 m for distance 2.5 km.

Figure 5 which has the source mid-way from the top to the bottom of the water column also illustrates the effect that the conjugate pair of energy fronts crosses at the source depth, here at 38 m. In the other two examples which have the sources close to the top and the bottom, we can observe crossings close to the top and bottom but appear as doublets which are in fact group energy fronts corresponding to the initiation of traveling directly to the bottom and traveling the short distance to the top and then reflecting to the bottom. Had the source been very close to the top or bottom, the doublet effect disappears but is most pronounced at the mid-point. Needless to say conjugate pair group energy effect is much more dramatic for deeper oceans. Strong diffraction will cause the group fronts to appear to bend due to more pronounced diffraction and the crossing effect will obviously be more pronounced in weakly varying velocity profiles. The effect of the group front bending is reasonably pronounced for the Yellow Sea environment having the stronger gradient of the changes of the sound speed profile.

5. Summary

Pulse signals at suitable frequencies and band widths allows one to extract moderately accurate information of the ocean properties. Although the results are not as impressive as for the intermediate depths it nevertheless gives one a tomographycal tool to extract environmental parameters using "vertical acoustical profile" methods akin to the analogous seismic case. The precursors due to even weak surface duct appear to be very sensitive indicators of the shallow water environment and could prove to be powerful oceanographic tools. Range-independent modeling of such environments will make the understanding of surface duct propagation more complete. Further investigation and comparison with data may prove fruitful in studying these kinds of environments.

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