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P - 337

Wave Equation Based Deghosting of OBC Data

***Jagmeet Singh*[†]*, K. Subramanyam*['][*] *and C.H. Mehta*["]**

[†]*Geopic, ONGC Ltd, Dehradun, 'Spic, ONGC Ltd, Panvel ,* ["] *Paradigm Geophysical, Mindspace, Malad (E),Mumbai*
Email:ksbkaredale@yahoo,cin

Summary

A 2D filter approach for deghosting of OBC data is presented. The filter designed in f-k space does away with the 1D assumption of vertical bouncing of rays in the water column.

Introduction

Towed streamer operations in congested areas lead to gaps in 3D coverage making the OBC (Ocean Bottom Cable) method employing detectors on the ocean bottom a necessity. In order to ensure that high quality seismic data is obtained using this method one has to address the problem of water column reverberation at the acquisition stage itself. Every primary arrival at a detector location is followed by secondary arrivals due to reverberation of the seismic energy between the water surface and water bottom. If the water depth is small (typically below 10m), the time gap between the primary and secondary arrivals is small and the undesired secondaries can be removed by deconvolution algorithms.

However if the water depth is high, one has to devise other ways to remove the multiples. One such solution, for removal of the receiver-side ghost, is to record both geophone and hydrophone data at every receiver location. Since the geophone records velocity whereas the hydrophone records pressure, the sum of the two is devoid of the downgoing part of the wavefield which is recorded with opposite polarities on the hydrophone and geophone. In frequency domain terms, there are notches in the frequency spectrum of hydrophone data, at $f = n\, f_0$, where $f_0 = v/2z$ (v is the acoustic velocity in water and z is the receiver depth), which fall within the seismic bandwidth for large water depths. The notches in the geophone spectrum occur at $f=(n+1/2)f_0$. Thus the sum of the two spectra is free of notches.

Most of the earlier methods aimed at deghosting were scalar methods. A scalar was designed to be multiplied with the geophone data in such a way that the autocorrelogram of the sum of hydrophone and geophone data was as spiky as possible(Barr and Sanders(1989), Dragoset and Barr(1994) , Barr(1997)). Clearly, these methods were inadequate as shown by the results obtained from such methods. Hydrophone and geophone response are different, and geophone ground coupling varies from place to place making it clear that a filter should be designed and applied to either of the two (preferably geophone) before the two are summed.

One such filter based technique has been suggested by Robert Soubaras (1996). A couple of techniques in which the geophone is phase shifted by 90 degrees prior to the design of an appropriate filter has been suggested by the present authors (2004). One of the techniques is identical to that of Robert Soubaras except for the initial phase shift, while in the other, the only step that follows the phase shifting is matching of hydrophone and geophone amplitude spectra. In both of the above papers, however, vertical or near vertical bouncing of rays in the water column is assumed. In order to achieve that, with increasing offset, one has to go deeper i.e. take design windows deeper in designing the filter. Apart from the fact that 1-D assumption is never really met, one may be left with a very small time window to meet this assumption as one goes deeper. In the present paper, we have done away with the 1D assumption and treated the problem in a 2D manner via the wave equation.

The paper is organized as follows. In section 2, we discuss the design of the 2D filter. Three possible methods have been suggested in this section. The results obtained from these methods are presented and discussed in the 'results and discussion' section. This is followed by conclusions.

Designing the filter

Figure 1 shows incident wavefield I(z) just at the water bottom, where the delay z corresponds to the sampling interval. If U and D denote upgoing and downgoing wavefields, then the hydrophone and geophone record pressure H and velocity G respectively given as

$$H = U + D$$

$G = (U - D)/ I_0$, (1)
where I_0 is the acoustic impedance of water bottom. From the formulae (1) above we see that if D=0, H and G seem to be in phase. Pressure (related to acceleration) and velocity measurements, however, must have a phase difference of 90 degrees. So we have to bear in mind, at the outset, that phase shifting is required. In the following, it is assumed that the geophone data has been appropriately phase shifted.

We start with the acoustic wave equation

$$\partial^2 \psi / \partial x^2 + \partial^2 \psi / \partial z^2 = (1/c^2(z))\partial^2 \psi / \partial t^2, \quad (2)$$

where $c^2(z)$ denotes the velocity of the wave through the medium. The ψ above is taken to be a function of the source-receiver offset x, depth z and time t. Fourier transforming ψ as follows

$$\psi(x,z,t) = \int\int d\omega\, dk_x\, \psi'(\omega, k_x, z) \exp\{i(\omega t - k_x x), \quad (3)$$

and substituting in (2) we get

$$\partial^2 \psi' / \partial z^2 = -k_z^2 \psi', \quad (4)$$

where $k_z = (\omega^2/c^2 - k_x^2)^{1/2}$. (5)

For a constant velocity medium like water, the solution may be written as

$$\psi'(\omega, k_x, z) = D(\omega, k_x) \exp(ik_z z) + U(\omega, k_x) \exp(-i k_z z), \quad (6)$$

where the symbols D and U denote downgoing and upgoing waves. We note from the above that the phase factor for upward continuation of upgoing waves or the downward continuation of downgoing waves is $\exp(ik_z z)$.
For a primary $I(\omega, k_x)$, the upgoing and downgoing parts of the wavefield may be written as

$$U(\omega, k_x) = I(\omega, k_x)[1-R \exp(2i k_z d) + R^2 \exp(4i k_z d) - R^3 \exp(6i k_z d) + \ldots],$$

$$D(\omega, k_x) = I(\omega, k_x)[-\exp(2i k_z d) + R \exp(4i k_z d) - R^2 \exp(6i k_z d\} + \ldots], \quad (7)$$

where R is the water bottom reflectivity and reflection coefficient at sea surface(water to air) is taken to be -1.

Using (1) (and dropping I_0 from the formula for G) we get

$$H = \{ (1-\exp(2i k_z d))/(1+R \exp(2i k_z d))\}I \quad (8)$$

$$G = \{(1+\exp(2i k_z d))/(1+R \exp(2i k_z d))\}I \quad (9)$$

So from the above, we see that

$$(1 + \exp(2i k_z d))\, H = (1-\exp(2i k_z d))G\, F, \quad (10)$$

where F is the desired filter. From (10), F is given as

$$F(\omega, k_x) = (1+\exp(2i k_z d))/(1 - \exp(2i k_z d)).\, H(\omega, k_x)/G(\omega, k_x) \quad \ldots(11)$$

Once the spectra are matched, a scalar needs to be applied to get at the primary. The scalar required follows from (8) and (9). We see that

$$H(\omega, k_x) + \{(1+R)/(1-R)\}\, G(\omega, k_x) = (2/(1-R))\, I(\omega, k_x). \quad \ldots(12)$$

From the above equation we see that the required scalar (1+R)/(1-R) accomplishes the rest of the job once filtering is done. Note that the reflection coefficient above has been taken to be independent of angle of incidence.

A subtle point needs to be explained here. If one applies the filter F to geophone data directly, it would mean division (see denominator in F) followed by multiplication by G. That in turn means that one would effectively be dealing with the hydrophone data only! A way out is to inverse Fourier transform the L.H.S. and R.H.S. of equation (10) back in time and design a Wiener filter in the time-domain. A possible approach in the frequency-domain is the following. As stated at the beginning of section 2, G in equation (10) is a phase shifted one (phase shifted by 90 degrees). We believe that no further phase shifting is required at zero depth d. So, when we design our filter $F(\omega, k_x)$, we use amplitude spectra $|H(\omega, k_x)|$ and $|G(\omega, k_x)|$ in place of $H(\omega, k_x)$ and $G(\omega, k_x)$ in equation (11). Although this approach is less satisfactory than the time-domain approach from a theoretical standpoint, results obtained from it are good.

Both the techniques have been used in the present paper, and in their 1-D avatar, in our earlier paper (2004). Still another way to obtain the primary follows from equation (8). One can just invert equation (8) to find the primary I at one stroke. Results from this approach are also presented. Note that the depth of water varies smoothly within a CDP gather and d above has been taken to be the mean depth. This may not be justified in an area where water depth variations are larger. Extending the calculation to accommodate depth variations in such an area is possible and would be taken up in a forthcoming publication.

Results and Discussion

Figure 2 shows alternate hydrophone and geophone gathers obtained from two receiver lines used in swath shooting. The sum of hydrophone, geophone gathers using frequency-domain approach discussed above is shown in figure 3. Mitigation of secondaries is clearly seen. Results of the same approach on synthetic gathers (figure 4) are shown in figure 5. Figure 6 shows section obtained from stacking hydrophone data only whereas figure 7 shows the stack obtained from frequency-domain approach. Figure 8 shows stack obtained from the time-domain approach.

Figure 9 shows the output from our method no. 3 in which we obtain the primary directly from equation (8). Figure 10 shows the stack obtained from one of the proprietary softwares available with ONGC, which we have used as a benchmark. Our results compare well with this benchmark. In order to compare our three methods, we have also included the amplitude (and phase) spectra of outputs obtained by these methods (figs. 11-13). We see that the notches in the hydrophone spectra (roughly around 20 Hz and 40 Hz) have been best removed by the frequency-domain method. Method no. 3 in which primary is obtained directly from hydrophone has not been able to remove the notches. Figures 14-16 show averaged autocorrelations obtained from outputs from our three methods. Again, we note that the frequency domain method has worked the best.

Conclusions

Three techniques for deghosting of OBC data that take care of the slant paths in the water column have been tested. From this preliminary study, results obtained from the frequency-domain approach seem to be the best. Further work is in progress to fine-tune these methods.

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N.B. The views expressed here are the views of the authors only and do not reflect the views of ONGC Ltd.

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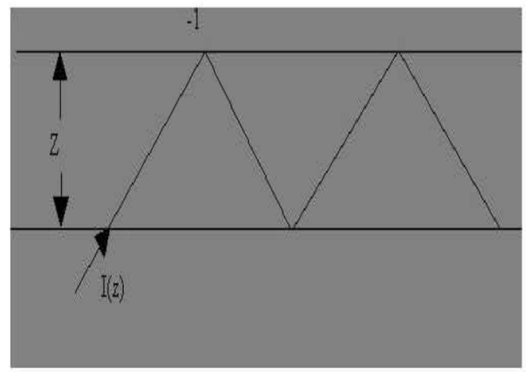

Figure 1: Incident wavefield I(z) shown bouncing back and forth between sea bottom and surface.

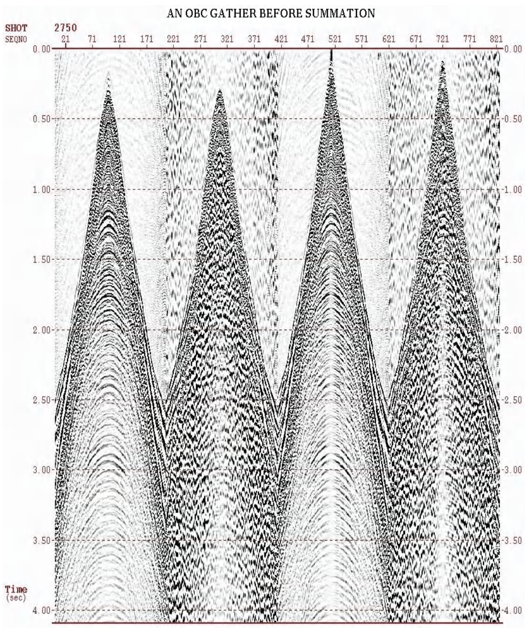

Figure 2 : Alternate hydrophone and geophone gathers from two receiver lines.

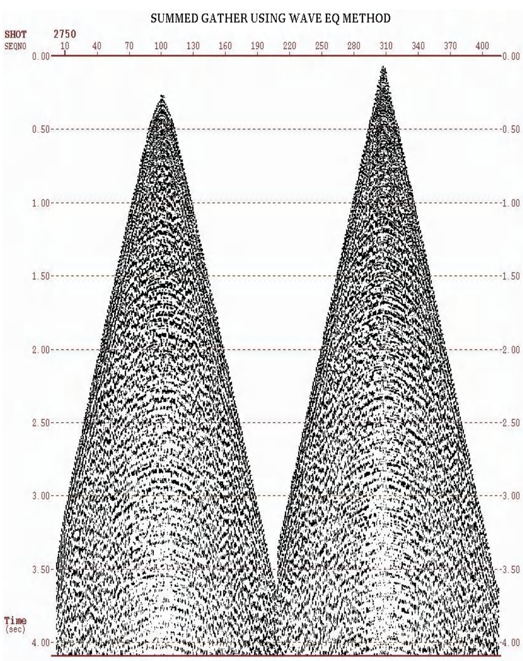

Figure 3 : Sum of hydrophone, geophone gathers shown in figure 1 using frequency-domain approach.

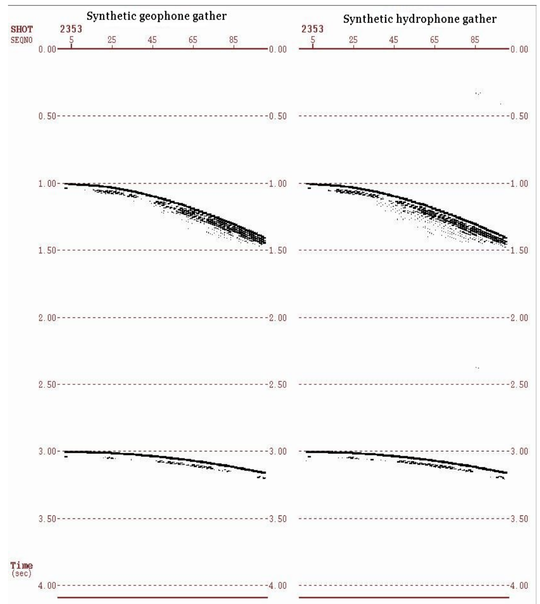

Figure 4 : A pair of synthetic hydrophone, geophone gathers.

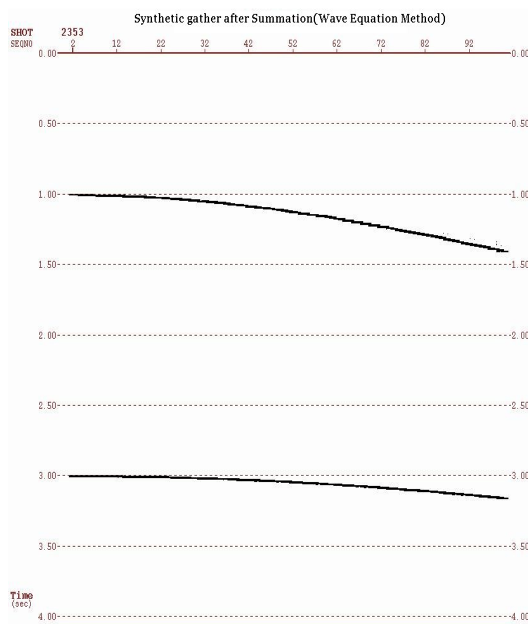

Figure 5 : Sum of the pair in figure 3 using frequency-domain approach.

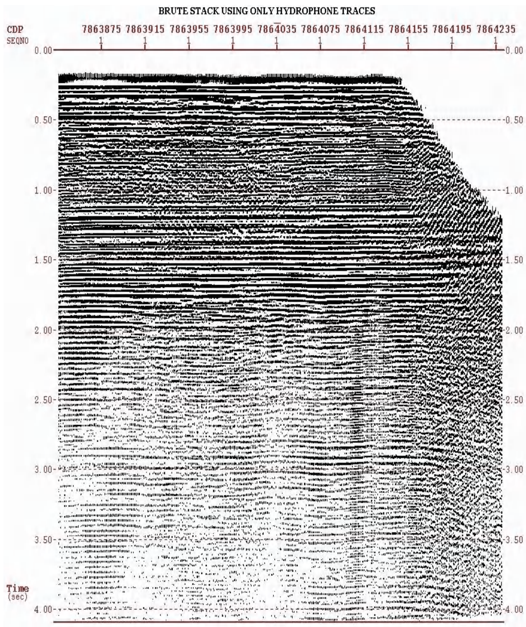

Figure 6 : Stack obtained using hydrophone gathers only.

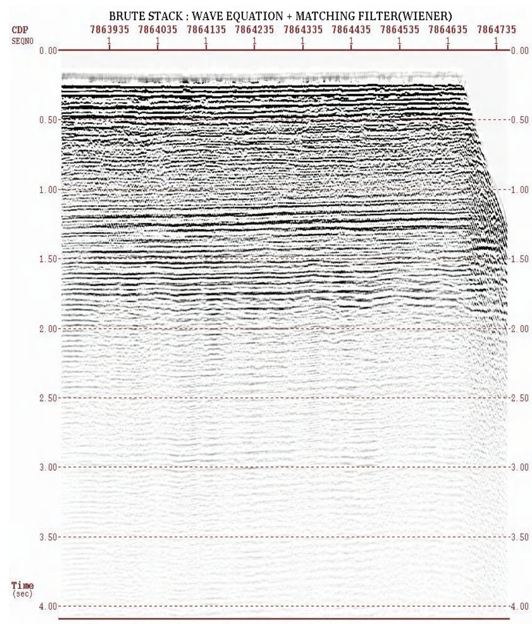

Figure 8 : Stack obtained using time-domain approach.

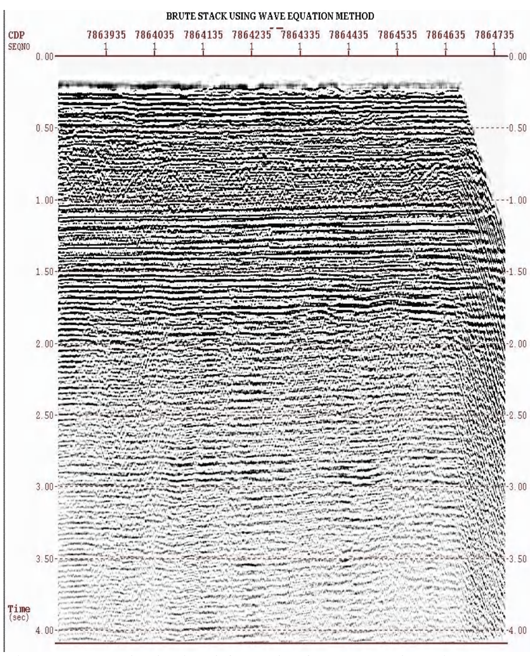

Figure 7 : Stack obtained from the frequency-domain approach.

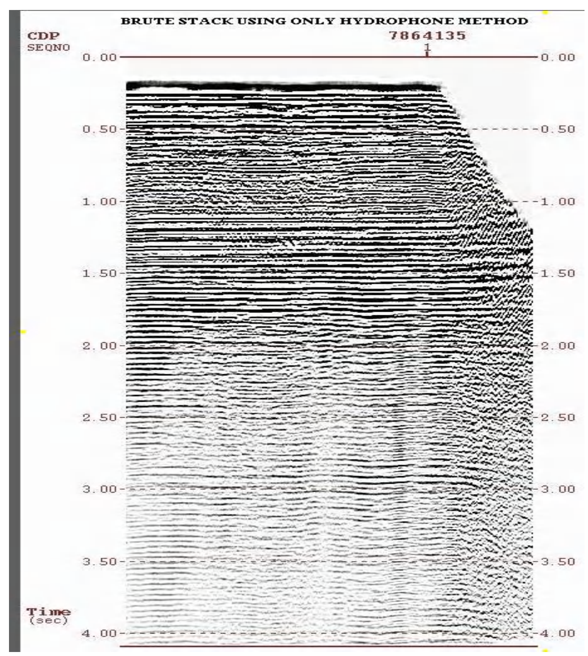

Figure 9 : Stack obtained using equation (8), i.e. obtaining the primary directly from the hydrophone data

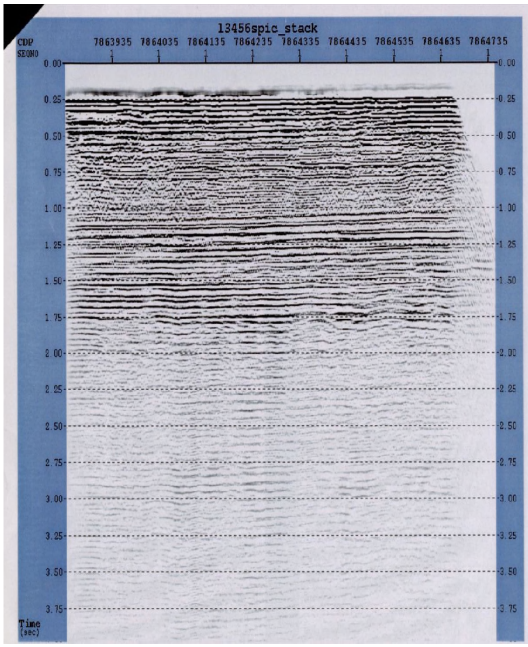

Figure 10 : Stack obtained from one of the proprietary softwares available with ONGC.

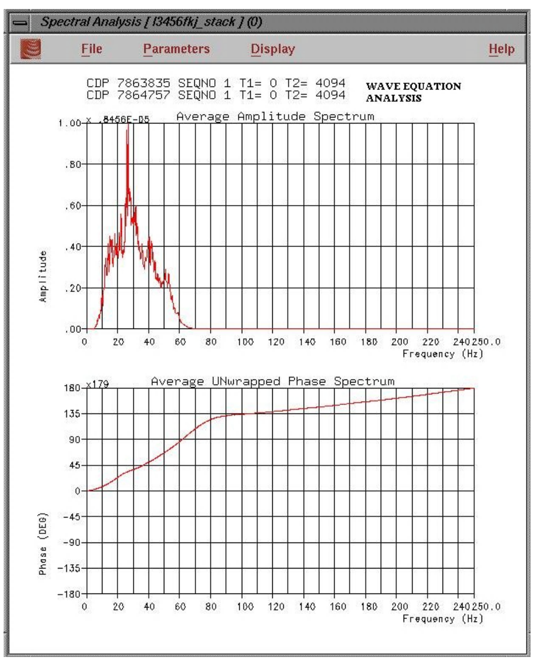

Figure 11:Amplitude and phase spectrum--frequency-domain approach.

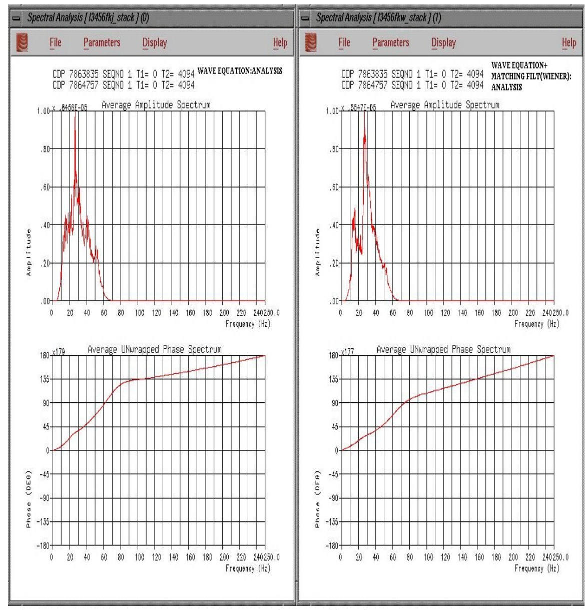

Figure 12 : A comparison of amplitude spectra obtained from frequency-domain approach(left panel) and time-domain approach(right panel).

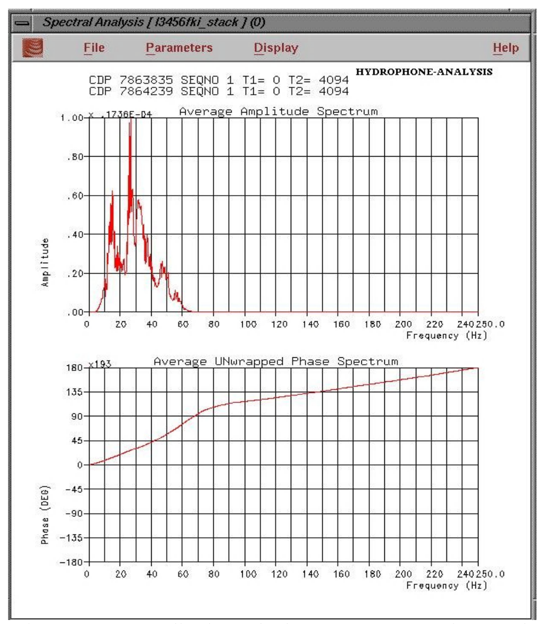

Figure 13 : Amplitude and phase spectrum—primary obtained directly from equation (8) using hydrophone data only.

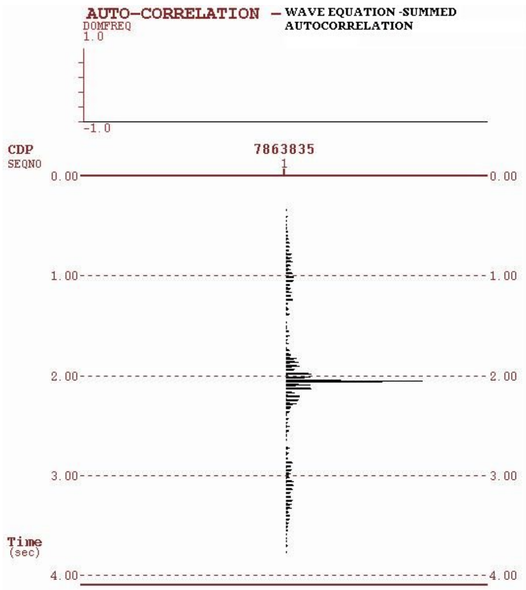

Figure 14 : Autocorrelation(averaged) of the output obtained from frequency-domain approach

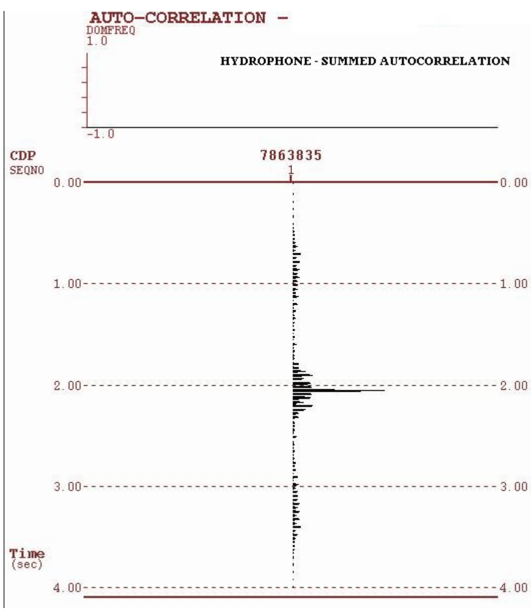

Figure 14 : Autocorrelation (averaged) of the output obtained from method no. 3 i.e. primary obtained directly from hydrophone data using equation (8).

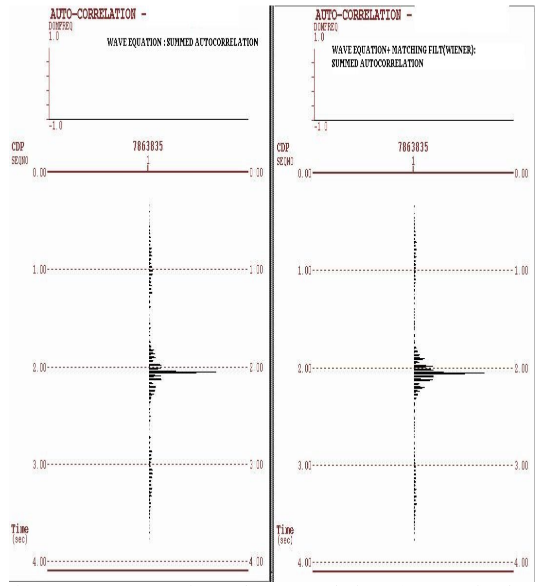

Figure 16 : A comparison of autocorrelations (averaged) of outputs obtained from frequency-domain approach (left panel) and time-domain approach (right panel).