Simultaneous Demultiple of 4C OBC Data

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Summary

This paper exposes a new approach to the removal of sea surface related multiples in four component (4C) ocean bottom cable (OBC) data. The essential idea comes from the following realization: in the Fourier and Hankel transformed domains, the de-multiple operator is the same for all components of the OBC data. The operator can be estimated from the hydrophone data alone, provided that the ocean bottom is flat and a reliable source signature is available or can be estimated. Under these assumptions, the method is independent of the property of the sediments below the ocean bottom and recovers primary events overlapped by multiples. We demonstrate the method through synthetic and real data examples.

Introduction

Suppression of sea surface multiples in conventional marine streamer data have been studied extensively. Early observation and analysis of trapped sound wave energy in shallow waters were given by Pekeris (1948) in terms of normal modes. Backus (1959) treated water reverberation problem as linear filtering process and proposed its elimination by inverse filtering. Riley and Claerbout (1976) introduced the prediction error filter technique for multiple suppression in 2D acoustic medium. Kennett (1979) considered the problem in elastic layers by comparing the full wave solutions with and without the free elastic surface.

Berkhout (1982) and Verschuur etal (1992) treated the surface multiple generation and elimination as a feedback system and proposed the prediction then subtraction scheme. A particular implementation of the Delft scheme was demonstrated favorably against other techniques on real data by Hadidi etal (1998). This procedure is implemented as Kirchhoff integral and requires separation of up- and down-going waves. Dragoset and Jericevic (1998) give some excellent perspective on the prestack inversion approach. Carvalho etal (1992) proposes to use the Born scattering series approach. This method works with two-way wave field.

In contrast to the large body of references of multiple suppression on streamer data, less attention has been given to the problem of multiple removal in four component (4C) ocean bottom cable (OBC) data, especially the horizontal components which contain shear wave information. This is probably due to the relative new existence of 4C-OBC experiments. Nevertheless, Barr and Sanders (1989) considered the combination of dual sensor data (hydrophone and vertical geophone) to suppress surface multiples by noticing a reverse polarity of the multiples in the two recordings. The ocean bottom sediment property is required to estimate the combination factor. This method has found some use in 4C OBC data by combining the pressure and vertical velocity recordings to improve imaging quality.

The real potential of the 4C OBC data, however, lies in the analysis and comparison of each component for AVO verification and reservoir attribute extraction and reservoir monitoring. Because the primary shear wave reflections tend to overlap with P-wave multiples, the removal of multiples becomes critical if shear wave analysis is to be carried out. Some very recent work on removing multiples in individual components include Soubaras (1998) and Ikelle (1998).

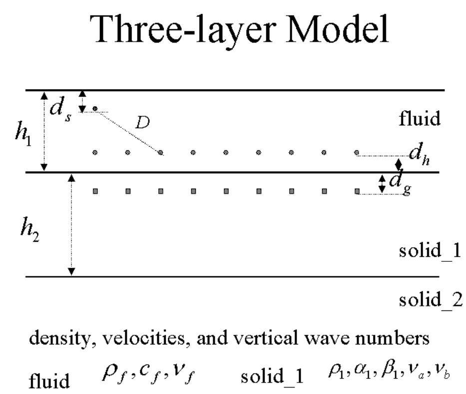

Fig. 1: The conceptual 3-layer model used to derive the demultiple operator for 4C OBC recordings. Hydrophones and geophones are assumed to be in water and in solid, respectively, with small distances from the ocean bottom.

The elimination of sea surface multiples in 4C OBC data is addressed in this paper. The approach taken is an extension to Kennett (1979). First, the full wave solution is obtained for the boundary/initial value problem in two three-layer media. In the case of a fluid layer over one elastic layer and one elastic half space, the solution represents the OBC data with sea surface multiples. In the case of a fluid half space over the two elastic media, the solution is the desired results of a demultiple operator. Comparison of the two solutions will lead to this demultiple operator. The method is demonstrated with synthetic and real data examples.

The Hydrophone and Geophone Recordings

The three-layer model in Figure 1 is considered to derive the analytic expression for the full wave recordings of the hydrophone and geophones. Any additional layers can be easily incorporated in the generalized reflection coefficients at the solid/solid interface. The strategy is as follows:

Firstly, the source wavefield is decomposed into a summation of plane waves according to the Sommerfeld integral. A spherical wave is expressed as the zero-th order Hankel transform of plane waves. In our case, the source is normally an airgun fired in fluid. Refering to Figure 1, the source wavefield can be expressed in the frequency domain as

$$\frac{e^{i\frac{\omega}{c_f}D}}{D} f(\omega) = i\, f(\omega) \int_0^\infty \frac{e^{i\nu_f |z-d_s|}}{\nu_f}\, k J_0(kr) dk. \qquad (1)$$

We have assumed $z = 0$ at the sea surface and $r = 0$ at the source point. The horizontal and vertical wavenumbers are denoted by k and ν_f. And $\omega^2/c_f^2 = k^2 + \nu_f^2$. $D = \sqrt{r^2 + (z-d_s)^2}$ is the distance of the observation point to the source.

Secondly, taking the zero-th order Hankel transform of these source wavefield leads to plane waves in the frequency and wavenumber (f-k) domain. The factor $e^{i\nu_f|z-d_s|}$ can be preceived as vertical propagation of plane wave from the source. The $if(\omega)/\nu_f$ factor is the amplitude of the plane waves. The propagation of source wavefield through the stack of layers can be studied using propagator matrices or the reflectivity methods (e.g., Müller, 1985). The hydrophone (pressure) and geophone (particle velocity) recordings in time-space domain are then obtained by inverse Fourier and Hankel transforms.

$$P(t,r) = \int_{-\infty}^{\infty} d\omega e^{-i\omega t} \int_0^{\infty} P(\omega,k)\ kJ_0(kr)dk, \quad (2)$$

$$V_R(t,r) = \int_{-\infty}^{\infty} d\omega e^{-i\omega t} \int_0^{\infty} V_R(\omega,k)\ kJ_1(kr)dk, \quad (3)$$

$$V_Z(t,r) = \int_{-\infty}^{\infty} d\omega e^{-i\omega t} \int_0^{\infty} V_Z(\omega,k)\ kJ_0(kr)dk. \quad (4)$$

It is worth noting that the horizontal geophone component needs to be forward and inverse transformed using the first order Hankel transform.

solution with multiples

In considering Figure 1, the recorded pressure at the hydrophones and the velocity of particle motion at the geophones can be expressed in the ω-k domain as the following.

$$P(\omega,k) = 2\lambda_0(\omega,k)\frac{e^{i\nu_f h_1}}{1+\hat{R_{pp}}e^{2i\nu_f h_1}}\frac{\sin(\nu_f d_s)}{\nu_f} \quad (5)$$

$$V_r(\omega,k) = -2i\lambda_1(\omega,k)\frac{e^{i\nu_f h_1}}{1+\hat{R_{pp}}e^{2i\nu_f h_1}}\frac{\sin(\nu_f d_s)}{\nu_f} \quad (6)$$

$$V_z(\omega,k) = -2i\lambda_2(\omega,k)\frac{e^{i\nu_f h_1}}{1+\hat{R_{pp}}e^{2i\nu_f h_1}}\frac{\sin(\nu_f d_s)}{\nu_f} \quad (7)$$

where,

$$\begin{aligned}
\lambda_0(\omega,k) &= \rho_f\omega^2 f(\omega)[\hat{R_{pp}}e^{i\nu_f d_h} + e^{-i\nu_f d_h}] \\
\lambda_1(\omega,k) &= \omega f(\omega)(\mathbf{p}^d + \mathbf{p}^u \cdot \underset{\sim}{\mathbf{E_1}} \cdot \underset{\sim}{\mathbf{R_2}} \cdot \underset{\sim}{\mathbf{E_1}}) \cdot \hat{\mathbf{T}}_\mathrm{d} \\
\lambda_2(\omega,k) &= \omega f(\omega)(\mathbf{q}^d + \mathbf{q}^u \cdot \underset{\sim}{\mathbf{E_1}} \cdot \underset{\sim}{\mathbf{R_2}} \cdot \underset{\sim}{\mathbf{E_1}}) \cdot \hat{\mathbf{T}}_\mathrm{d}
\end{aligned}$$

The row vectors $\mathbf{p}^{u,p}$ and $\mathbf{q}^{u,p}$ are the projection vectors for the up- and down-going P and S waves, respectively. $\underset{\sim}{\mathbf{E_1}}$ is the phase shift matrix of the 2nd layer. $\hat{\mathbf{T}}_\mathrm{d}$ is the downward transmission vector through the ocean bottom. $\hat{R_{pp}}$ denotes the general P-P reflection coefficient at the ocean bottom. $\underset{\sim}{\mathbf{R_2}}$ stands for the reflection coefficient matrix at the bottom of the 2nd layer, which can be generalized to include more elastic layers.

solution without surface multiples

The desired response of surface multiple elimination, is the response without the free fluid surface. They are

$$DP(\omega,k) = i\lambda_0(\omega,k)e^{i\nu_f h_1}\frac{e^{-i\nu_f d_s}}{\nu_f} \quad (8)$$

$$DV_r(\omega,k) = \lambda_1(\omega,k)e^{i\nu_f h_1}\frac{e^{-i\nu_f d_s}}{\nu_f} \quad (9)$$

$$DV_z(\omega,k) = \lambda_2(\omega,k)e^{i\nu_f h_1}\frac{e^{-i\nu_f d_s}}{\nu_f} \quad (10)$$

The Demultiple Operator

Comparing the desired results with actual recording, we have the one operator that can be appllied to both the hydrophone and geophone recordings

$$O(\omega,k) = \left(1+\hat{R_{pp}}e^{2i\nu_f h_1}\right)\frac{ie^{-i\nu_f d_s}}{2\sin(\nu_f d_s)} \quad (11)$$

$$DP(\omega,k) = O(\omega,k)P(\omega,k), \quad (12)$$

$$DV_r(\omega,k) = O(\omega,k)V_r(\omega,k), \quad (13)$$

$$DV_z(\omega,k) = O(\omega,k)V_z(\omega,k). \quad (14)$$

The operator has two parts: removing the ghost and removing the reverberation. Given water depth, airgun and hydrophone depth, one can estimate this operator from the hydrophone recording.

$$O(\omega,k) = \frac{2\rho\omega^2 f(\omega)\sin[\nu_f(h_1-d_h)]e^{-i\nu_f d_s}}{2\rho\omega^2 f(\omega)\sin(\nu_f d_s)e^{-i\nu_f(h_1-d_h)} - \nu_f P(\omega,k)} \quad (15)$$

Since we chose $f(\omega)$ to represent the source function for displacement potential, $\rho\omega^2 f(\omega) \equiv S(\omega)$ is the source function for pressure field. In most field conditions, $d_h \sim 0$. The operator takes the following form

$$O(\omega,k) = \frac{2S(\omega)\sin(\nu_f h_1)e^{-i\nu_f d_s}}{2S(\omega)\sin(\nu_f d_s)e^{-i\nu_f h_1} - \nu_f P(\omega,k)} \quad (16)$$

The operator becomes unstable when $\nu_f = 0$. This is caused by the deghost part of the operator. Commonly referred to as "ghost notch", the problem is normally dealt with by adding a small number to the denominator. Errors are introduced by this procedure and no recovery is possible.

This problem is overcome here by introducing a small imaginary part to the frequency. The deghost operator is unconditionally stable. The effect of the small imaginary part can be removed at the time of inverse Fourier transform.

Implementation and Considerations

The implementation and some numerical considerations are demonstrated through Figure 2. Inputs include 4C common-shot or common-receiver gathers, source time function and related acquisition parameters. In the editing step, interpolation and geophone rotation are performed. Each trace is multiplied with $e^{-\omega_i t}$ to avoid instability, where ω_i is the small imaginary part for frequency. Typically $\omega_i = \pi/t_{max}$ and t_{max} being the maximum recording time. These traces and the source time function are Fourier-transformed. For each frequency, we then

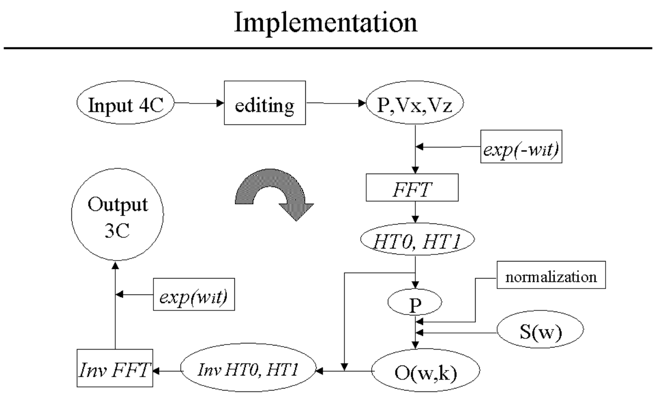

Fig. 2: Diagram showing the implementation of 4C OBC demultiple.

take the zero-th order Hankel transform of the pressure and vertical velocity data and, take the first order Hankel transform of the horizontal velocity data. For each frequency and wavenumber pair, we estimate the demultiple operator from the pressure data and apply the operator to all components at each $f-k$ pair. We then take the inverse Hankel transform: zero-th order for $P(\omega,k)$ and $V_Z(\omega,k)$ and first order for $V_R(\omega,k)$. After inverse FFT and Removal of $e^{-\omega_i t}$ effect, we obtain the demultipled 3C data.

Figure 3 shows a 3-layer synthetic example to validate the above implementation procedure.

A North Sea Data Example

This experiment consists of a 3 km 4C ocean bottom cable. The source boat traverses a distance of 9 km. The cable was moved three times in order to have good coverage. Figure 4 show the position of one cable layout and the track of source boat. From the figure, it seems that common-shot gathers may be more suitable for demultiple application than common receiver gathers. However, aperture limitation and missing near offsets in the common shot gathers requires the use of common receiver gathers. The source signature was obtained from array modeling. Source depth is 6 m and water depth in the area is 121 m.

Figure 5 shows the horizontal geophone data before (top) and after (bottom) surface related multiple removal. The results suggest improvement in the shallow events (above 2.5 sec) and overall section quality.

A remaining challenge in applying the procedure in Figure 2 lies in the difficulty of obtaining a reliable normalization factor to the hydrophone data. This factor is required to scale the hydrophone data so that the source can be treated as *unit* point source. If the normalization factor is known, then the demultiple procedure is truely independent of the ocean bottom property. This factor can be measured with a suspended hydrophone at some water depth. Otherwise, an inversion procedure needs to be devised to derive this factor.

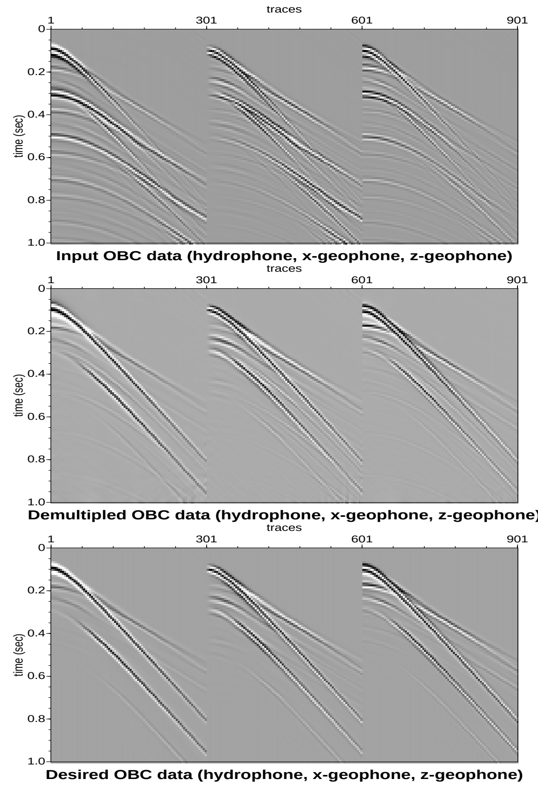

Fig. 3: Input synthetic data (P,X,Z) from a 3-layer model (top), the data after demultiple process of Fig. 2 (middle), and the desired demultiple results (bottom). Note the strong converted waves and its multiple.

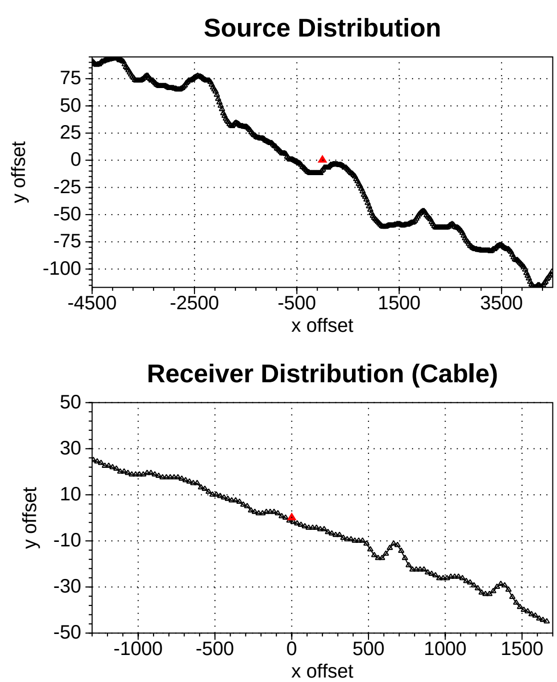

Fig. 4: The source (top) and cable (bottom) locations for the North Sea Experiment. Grey triangles represents the CSG and CRG used for demultiple applications.

Conclusions

Based on the flat earth model, a procedure is presented to simultaneously remove multiples in 4C OBC data. It is based on the observation that demultiple operators are the same for all components in the frequency (Fourier) and wavenumber (Hankel) domain. Given a reasonable normalization factor, the operator can be estimated from hydrophone data alone and then applied to all other components. Synthetic and real data examples validate the proposed approach. For more complicated ocean bottom geometries, improvement over the current approach is required.

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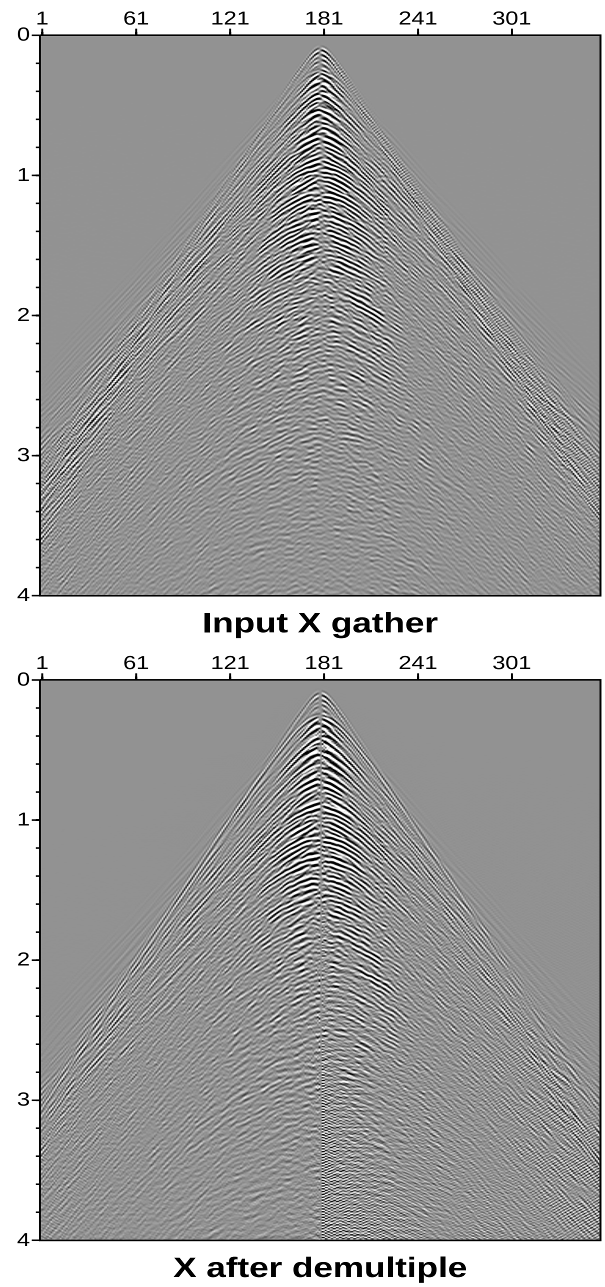

Fig. 5: The horizontal geophone data from a North Sea experiment before (top) and after (bottom) the multiple removal process. The demultiple operator is estimated from the hydrophone data in the $f-k$ domain, and applied to the horizontal geophone data in the $f-k$ domain.