Deghosting of over/under towed-streamer seismic data with wavefield extrapolation

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SUMMARY

In marine seismic acquisition, ghost effect due to the strong reflection of the sea surface causes serious notch trap in the spectrum. Ghost effect can be reduced by over/under towed streamer acquisition. However, most of deghosting technology for over/under streamer acquisition is based on seismic kinematics method, which cannot effectively solve the ghost wave interference and brings incomplete ghost suppression and distortion of the effective signal. In this paper, we propose a new deghosting method for over/under streamer acquisiton based on analytical *fk*-domain seismic wavefield extrapolation characterized by high computing efficiency. Cases studies of synthetic and real seismic datasets demonstrate that our seismic wavefield extrapolation based on Fourier transform ensures the consistency of the seismic amplitude and phase of over/under streamer seismic data and significantly eliminates the amplitude and phase error of far offset especially for the long streamer condition, which helps to decouple the real wave and the ghost wave and fill notch effect in the spectrum.

Key words: over/under towed-streamer, deghosting, seismic wavefield extraploation, frequency wavenumber domain.

INTRODUCTION

In conventional streamer marine seismic acquisition, the pressure sensor in a towed streamer records two wavefields that interfere with each other. The two wavefields are the upgoing pressure wavefield propagating directly to the pressure sensor from the streamer below, and the downgoing pressure wavefield reflected downwards from the free (sea) surface immediately above the streamer. The downgoing pressure wavefield like a "ghost" of the upgoing pressure wavefield. The receiver ghost from free surface cancels or degrades the signal at some frequencies, resulting steep notches in amplitude-frequency spectrum at low as well as high frequency. A streamer towed at shallow depth, the lower frequencies are strongly attenuated and cannot be recovered by a simple deconvolution as usually the swell noise is too strong, but it is good at receiving high-frequency components, because the frequency notches shifts to higher frequency. In contrast, a streamer at a deeper depth, it is good at receiving low-frequency components and the swell noise is normally strongly attenuated for it is exponentially decaying with depth, but the notching frequencies within the bandwidth hence limiting the useful frequencies.

In order to take advantage of both shallow and deep streamers, it has been proposed to record the pressure field at two different depths and to combine optimally all the measurements (Posthumus, 1993). Although the over/under method was introduced for about over a century (Haggerty, 1956), initial attempts in the North Sea were unsuccessful in the 1980s because the technology at that time was not advanced enough to keep the vertical paired cables accurately aligned (Sonneland et al., 1986). The success of the method for ghost removal depends on accurately maintaining the over/under streamers in the same vertical plane. For nearly 20 years, streamer technology has been developed that allows streamer steering and much more accurate positioning. Therefore, it is now possible to maintain Over/under cable acquisition techniques are seismic-acquiring techniques in which streamers are towed at different depths as vertically aligned pairs. The successful launch of the over/under method was enabled by the recent developments in the streamer technology (Hill et al., 2006; Moldoveanu et al., 2007). Various methods have been proposed to achieve deghosting using over/under acquisition configurations (Posthumus, 1993; Amundsen, 1993;Hill et al., 2006; Ferber, 2008; Ozdemir et al., 2008). The technique that is often used is the method of Posthumus(1993), it is referred to as the dephase and sum method by wavefield separation technique, it combines data from the over/under streamers into a single dataset such that the resulting data have the high-frequency characteristics of the conventional data recorded at a shallow cable depth and the low-frequency characteristics of the conventional data recorded at a deeper cable depth. Ozdemir et al. (2008) proposed a modified dephase and sum approach that optimized the SNR of the combination in the least squares sense by using an estimate of the noise level of the data recorded by deep and shallow streamers. There are another algorithms can remove the downgoing wave without explicit knowledge of the downgoing wave(Ferber, 2008), it shit the reach time of downgoing wave of the over and under streamer to the same, then subtract the downgoing wave. Although it leaves data with a pseudo calm-sea surface ghost, it eliminates time-variant perturbations due to the time-variant shape of the sea surface, especially in rough weather conditions.

In this paper, we propose a deghosting method of over/under streamer based on seismic wave equation continuation formula in the frequency wavenumber domain, which eliminate far offset signal calculation error of the long streamer contract to the traditional dephase and sum algorithm. The analytical seismic wave continuation based on Fourier transform ensure the consistency of the amplitude and phase of seismic signal from over/under streamer seismic acquisition with high computing efficiency, suppress the ghost signal that interference the up-going signal from the earth under water effectively and fill the notches in the amplitude spectrum. A synthetic single shot gather is used to verify the performance of the proposed method. Finally, we apply the proposed method on a real over/under marine dataset from China. The results show that the proposed method can simultaneously achieve good imaging of shallow and deep targets, seismic data wide frequency bandwidth by effectively suppressing the ghost.

METHOD AND RESULTS

The deghosting algorithm with wave equation continuation

The pressure wavefields(P) at the sea surface comprise respective upgoing wavefield (P_t^0)from the earth under water and downgoing pressure wavefield (P_g^0) , according to the condition of free boundary(sea surface) :

$$P = P_t^0 + P_g^0 = 0 \tag{1}$$

The pressure wavefields(P^1) at the depth Δz under the sea surface can be respected as the sum of P_t^0 propagate backward Δz and P_g^0 propagate forward Δz .In the frequency wavenumber (f-k) domain, it can be written as the following expression by using the wavefield extrapolation operators:

$$P^1 = P_g^0 \exp(ik_z \Delta z) + P_t^0 \exp(-ik_z \Delta z) \tag{2}$$

Hence, comining equations 1 and 2， the we have the following expression:

$$\exp(ik_z \Delta z) P^1 = P_t^0 (1 - \exp(2ik_z \Delta z)) \tag{3}$$

If the depth of streamer 1 (over) is z_1 and the depth of streamer 2 (under) is z_2 ,we have the the following expression:

$$\begin{cases} w^{n_1} P_1 = (1 - w^{2n_1}) P_t^0 \\ w^{n2} P_2 = (1 - w^{2n_2}) P_t^0 \end{cases} \tag{4}$$

Where $w = \exp(ik_z \Delta z)$, $n_1 = \dfrac{z_1}{\Delta z}$ and $n_2 = \dfrac{z_2}{\Delta z}$.

Hence we have the pressure wavefield P_1 from P_1 after wave equation continuation and the pressure wavefield P_2 from P_2 after wave equation continuation

$$\begin{cases} \mathrm{P}_1 = w^{n_1} P_1 = W_1 P_t^0 \\ \mathrm{P}_2 = w^{n2} P_2 = W_2 P_t^0 \end{cases} \tag{5}$$

the operators W_1 and W_2 , which are given by:

$$\begin{cases} W_1 = (1 - w^{2n_1}) \\ W_2 = (1 - w^{2n_2}) \end{cases} \tag{6}$$

In order to avoid the occurrence of spatial aliasing, continuation step length is defined by:

$$\Delta z \le \frac{\pi v}{2\omega} = \frac{v}{4f} \tag{7}$$

The velocity of the sea water is about 1500m/s, the conventional sample interval of time is 2ms,we can get the maximum of the continuation step length is 1.5m.

To find the optimal estimate of the upgoing wavefield P_t^0 , mathematically, the method can be written as:

$$P_t^0 = \frac{\overline{W}_1 \mathrm{P}_1 + \overline{W}_2 \mathrm{P}_2}{|W_1|^2 + |W_2|^2} \tag{8}$$

Where $\overline{W}_i$ denotes the complex conjugate of the operator W_i .

The following steps to compute the upgoing wavefield from pressure measurements acquired at different tow depths:

- denoise the seismic datesets of stream 1 and streamer 2.
- compute the pressure wavefield P_1 from P_1 by wave equation continuation
- Sum the over and under records using the formula 5.

Synthetic data example

For simplicity, we take a simple two-layered model with flat sea bottom as an example to test the method. There are only two layer in the model, one is sea water layer with the velocity of 1500m/s, the other layer is a earth layer with the velocity of 2500m/s, and the size of the model is 1000m*600m. Figure 1 show the synthetic seismic datasets of over/under towed streamer with depth 17m and 23m without direct wave and multiple wave and the f-k spectrum of the synthetic seismic datasets. It is easy to see the arrival time of reflect wave and ghost wave in the synthetic seismic recording of 17m streamer and 23m streamer is obviously different. It can be also shown that the difference value between the up-going wave and the ghost wave at near offset and far offset increases, therefore the interference of up-going wave and ghost wave enhanced. Because of the effect of the ghost, there are periodic notches in the frequency wavenumber amplitude spectra, which are caused by the ghost.

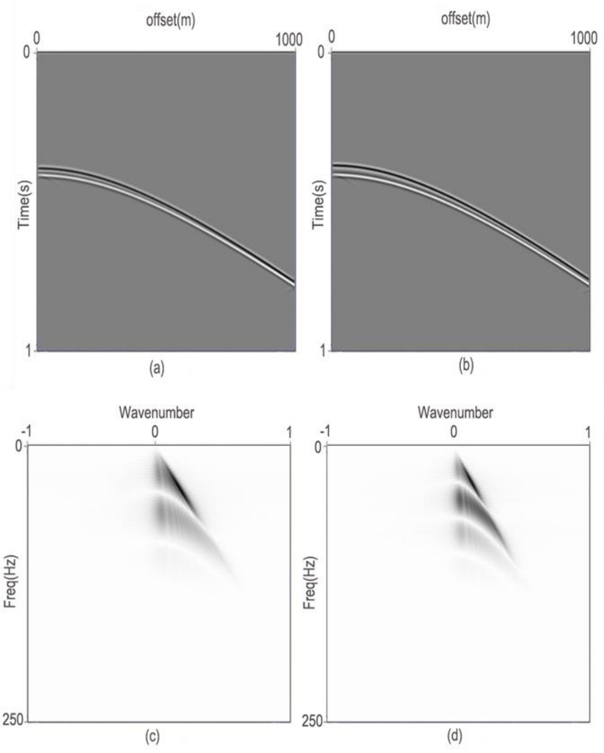

Figure 1. The synthetic seismic datasets of over/under towed streamer with depth 17m(a) and 23m(b) without direct wave and multiple wave .The f-k spectrum of the

synthetic seismic datasets in Figures 2a and Figure 2b is shown in Figure 2c and Figure 2d.

The result shot record obtained by the proposed method and the f-k spectrum of the result are shown in Figures 2a and 2b, respectively. It is clear that the proposed method can remove the ghost wave effectively and fill the notches well.

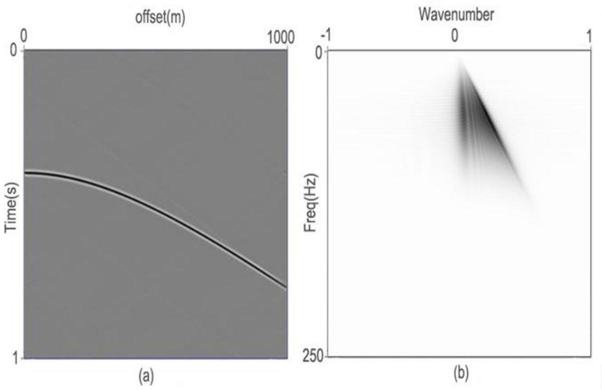

Figure 3. The result shot record obtained by the proposed method(a). The f-k spectrum of the result is shown in Figures 2a.

Real data example

To demonstrate the performance of the proposed method, we applied it on a real over/under dataset. The acquisition configuration of this dataset is set as following： An over/under source were deployed at 6 m depth and 12 m depth, and two streamers were deployed at depths of 17m and 23 m, respectively.

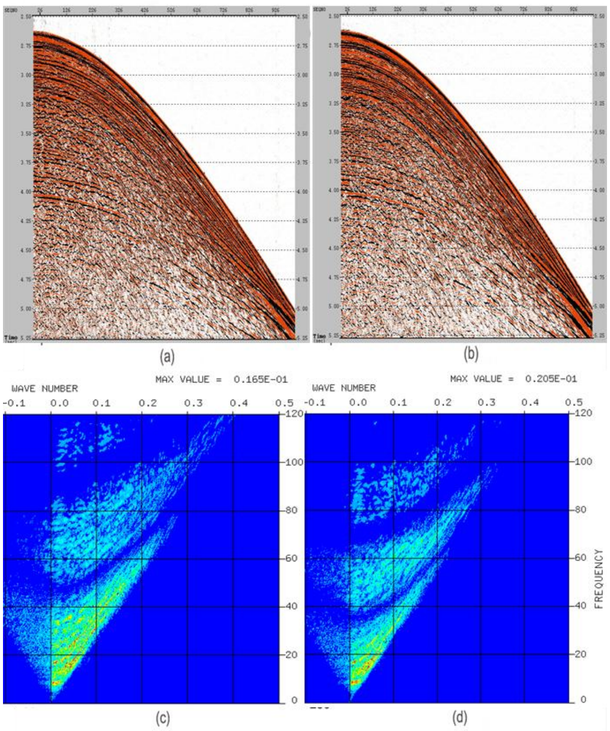

Figure 3. The shots after denoising at depths of 17 m(a), 23m(b), The f–k amplitude spectra of the shots in Figures 3a and Figure 3b is shown in Figure 3c and Figure 3d.

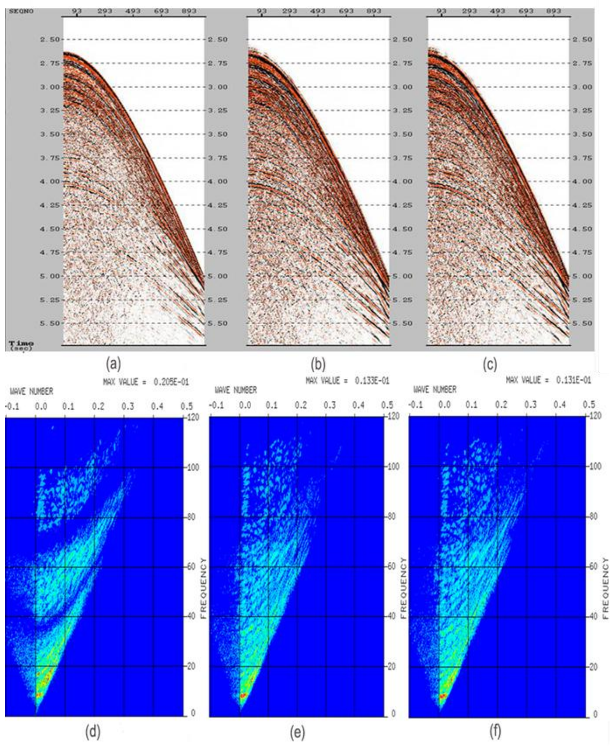

Figure 4. The shots after denoising at depth 23m(a), the combined results obtained by the traditional dephase and sum method(b)and the combined results obtained by the proposed method (c).The f–k amplitude spectra of the shots in Figures 4a, Figure 4b and Figure 4c is shown in Figure 3d, Figure 3e and Figure 3f.

Figure 3 shows the shots after denoising at depths of 17 m(a), 23m(b), and the f–k amplitude spectra of the shots at depths of 17 m(c), 23m(d), respectively. Figure 4 shows the shots at depth 23m(a), the combined results obtained by the traditional dephase and sum method(b)and the combined results obtained by the proposed method (c) and the f–k amplitude spectra(d)、(e)and(f) of the shots (a)、(b)and(c) in the same order. The comparison of Figures 4e and 4f shows that the result obtained by the proposed method has much richer frequencies components at big wavenumber. Furthermore, the notches at small wave number are well filled and the energy is also enhanced.

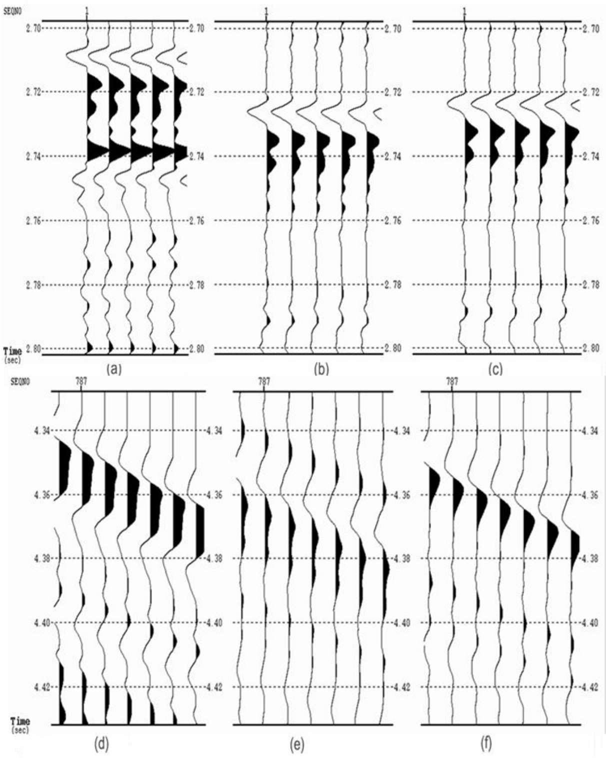

Figure 5. The near offset primary reflection wave of the seabed in the shots at depth 23m(a), the combined results obtained by the traditional method(b) and the combined results obtained by the proposed method (c) and the far offset primary reflection wave of the seabed in the shots at depth 23m(d), the combined results obtained by the traditional method(e) and the combined results obtained by the proposed method (f).

Figure 5 shows the near offset primary reflection wave of the seabed in the shots at depth 23m(a), the combined results obtained by the traditional dephase and sum method(b) and the combined results obtained by the proposed method (c) and the far offset primary reflection wave of the seabed in the shots at depth 23m(d), the combined results obtained by the traditional dephase and sum method(e) and the combined results obtained by the proposed method (f). In Figures 5a, the primary reflection wave is complex because of interference of bubble effect and source ghost, so the ghost of the primary reflection wave is complex. In Figures 5b and 5c, it is visible that both traditional dephase and sum method and proposed method can remove the ghost well. In Figures 5d, the primary reflection wave is only comprise of reflection wave and source ghost, because bubble effect is very weak at far offset. In Figures 5e, it is shown that the wave is so distort that it is not possible to find the reflection wave. in contrast , In Figures 5f, the reflection wave can be easy to distinguish, the wave are comprised of the reflection wave and the source ghost. Clearly the proposed method suppresses the receiver ghost better than the traditional method.

CONCLUSIONS

We proposed a deghosting method of over/under data with wave equation continuation. In the proposed method, the computing of the upgoing wavefield from pressure measurements acquired at different tow depths corresponding to wave equation continuation results from the data. Compared with the traditional methods, the proposed method has much richer frequencies components at big wavenumber. Furthermore, the proposed method suppresses the receiver ghost at far offset better. Synthetic and real data examples demonstrate that the proposed method can obtains a deghosting result with rich low and high frequencies and fill fill the notches in f-k amplitude spectra well.

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