In Search of the Primary Wavefield: Demultiple and Deghosting Applied to East Coast Marine Data

Richard Bale and Keith Wilkinson, Key Seismic Solutions Ltd.

Summary

Marine seismic data from the East Coast of Canada can pose processing challenges due to shallow water depth and hard water bottoms. We discuss two important steps that are necessary to obtain a broadband primary wavefield in these environments: multiple attenuation and deghosting. Our multiple attenuation, based upon the technique referred to as "Model-based Water Layer Demultiple", uses a two-pass methodology to ensure both source- and receiver-side peg-legs are treated correctly. Our deghosting method is applicable to variable depth of receiver below the sea surface. We illustrate application of both demultiple and deghosting on data acquired in the Flemish Pass area of East Coast Canadian waters.

Introduction

There is currently renewed marine exploration in offshore Canadian plays. This is therefore an opportune time to take a look at some of the key issues in processing marine data for these areas. Our present focus is on estimation of the *primary* wavefield, free of ghosts and multiples. Multiple attenuation is important as East Coast data typically suffers from strong multiple reverberations due to an unusually hard seafloor. Deghosting is desirable to extend the useable bandwidth, in particular for the low frequencies.

Surface Related Multiple Elimination or SRME (Verschuur et al., 1992) has been demonstrated to be effective for both 2-D and 3-D multiple attenuation, in moderate to deep water. However, it is well recognized that SRME can struggle with shallow water multiples, especially in the presence of a hard water bottom. The main reason for this is a mismatch in the predicted amplitudes between the high order water-layer multiples and peg-leg multiples from deeper reflectors. This leads to the failure of any adaptive subtraction procedure to simultaneously match all orders of multiple. SRME can in principle correct for this by iterative application. In practice this has its own problems, and is rarely done.

Consequently, a new breed of demultiple algorithm has been developed for shallow water, typically referred to as DWD ("Deterministic Water-layer Demultiple", Moore and Bisley, 2006) or MWD ("Model-based Water-layer Demultiple", Wang et al, 2011). Here, we discuss our own implementation for shallow water demultiple, which we also refer to as MWD, and highlight some shot-receiver asymmetry aspects which need to be handled carefully to obtain optimal results (see also Wilkinson and Bale, 2014).

In recent years, several solutions to the deghosting problem have been successfully demonstrated. These have been achieved through new *acquisition* methods (Carlson et al., 2007; Robertsson et al., 2008), through a combination of *acquisition* and *processing* (Soubaras, 2010; Poole, 2013), or recently through advances in *processing* only methods (Wang et al., 2013; Masoomzadeh et al., 2013).

Many recent surveys are designed to exploit acquisition advances. However, there are also many older surveys which can potentially benefit from a processing solution. Furthermore, acquisition solutions involving deep or variable towing depths require associated processing solutions to fill the resulting notches in the passband. A particular challenge for processing methods of deghosting is the variability of the streamer depth below the sea surface – either due to variations in the sea state, or to variations in the streamer tow depth, by design or by accident.

Here, we propose a new method for prestack deghosting that seeks to deal with the spatial variation in receiver depth, based on wavefield extrapolation.

Shallow Water Demultiple

Our method for shallow water demultiple is summarized here. More details are available in Wilkinson and Bale (2014). Figure 1 illustrates the principle. A Green's function is constructed using a model of the water layer from an interpreted seafloor, and Kirchhoff modelling. The Green's function can then be used to generate an additional bounce on either the shot or receiver side. The data contains primaries and multiples, so convolving with the Green's function converts primaries to first order multiples, and any multiples to higher order multiples. However, it is important to note that convolving with the Green's function on the shot side cannot possibly generate the multiples which only have receiver side bounces, nor vice versa. Therefore, in contrast to SRME, a two-step multiple prediction is required. Care must be taken that this is done in a way which doesn't double predict some of the multiples such as illustrated in Figure 1(c). This point is discussed by Lokshtanov (2001) and more recently by Kostov et al. (2015).

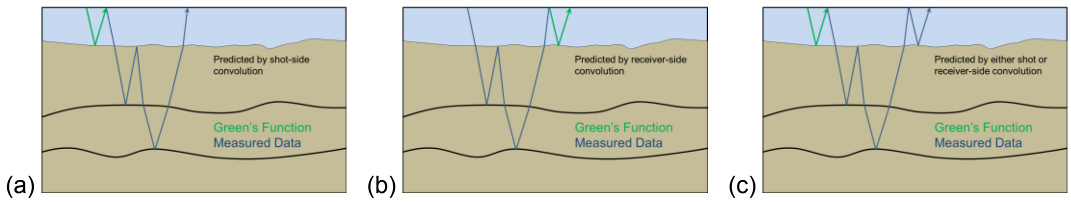

Figure 1. Construction of the water-layer multiple by using Green's functions (green) convolved with data (blue). This must be done separately for the shot side (a), and for the receiver side (b). Care must be taken to avoid double prediction of double sided multiples (c).

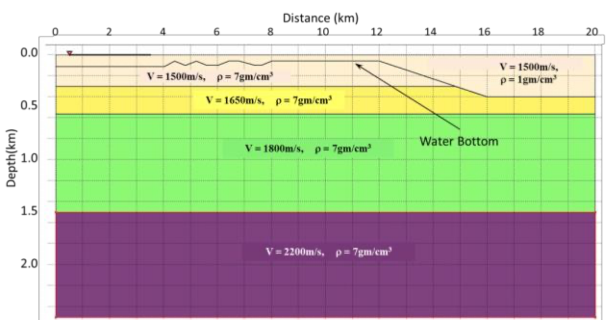

Figure 2. Depth model for synthetic.

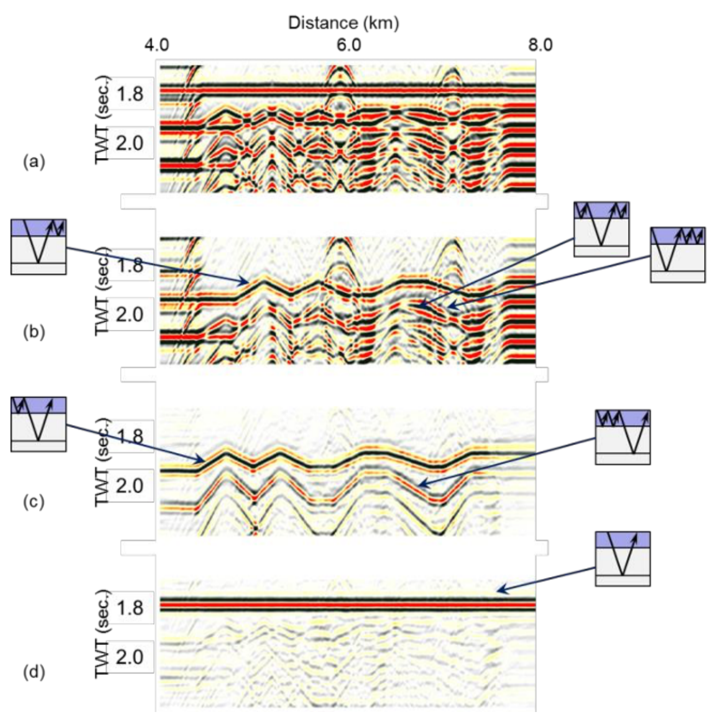

Figure 3. Steps in the MWD procedure. Shown are constant offset section (offset =587.5m) for: (a) input data; (b) predicted receiver-side multiples; (c) predicted shot-side multiples and; (d) the data after removal of both shot-side and receiver-side predicted multiples.

To illustrate our methodology, we apply MWD to a finite difference synthetic for the model shown in Figure 2. We focus on the area under the complex water bottom between 4km and 8km lateral position. Figure 3 shows a small section of a common offset section near the primary reflection for the interface at 1.5km depth. In Figure 3 we see: (a) the section before demultiple; (b) the predicted receiver-side multiples; (c) predicted source-side multiples after first removing the receiver-side multiples, and; (d) the resulting demultiple section with all water layer multiples removed. The raypath diagrams are used to indicate the various multiple types we can identify: they include receiver-side, source-side and both-side peg-legs. Note that because we have removed all multiples with a receiver-side bounce after (b), we see *only* source side multiples in (c).

Deghosting

Ghost events are generated at both the shot and receiver positions, due to downward reflection from the sea surface. Figure 4 illustrates the principle of the receiver ghost, showing the equivalence between a ghost reflection and a mirror receiver for the case of a flat sea surface. Interference between primary and ghost reflections creates notches in the spectrum and lowers the useable bandwidth. The time delay of the ghost is given in this simple case by $T = 2d\cos\theta/v$ where d is the depth of the receiver, v is water velocity and θ is the angle from the vertical of the up-going wave at the receiver.

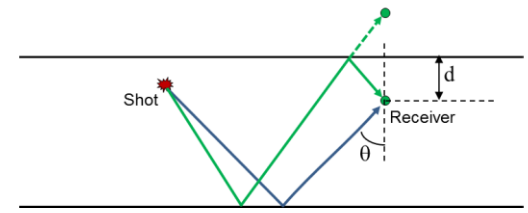

Figure 4. Receiver ghost geometry.

Defining u as the recorded wavefield, containing both up-going and down-going (ghost) arrivals, it is related to the up-going only wavefield u_0, using Z-transform notation, by

$$u = (1 + RZ)u_0 \ , \qquad (1)$$

where R is the free surface downward reflection coefficient, which must be negative and less than 1 in magnitude. Using $\cos\theta = \sqrt{1 - v^2 p^2}$, the delay operator can be expressed in terms of frequency and spatial wavenumber $k_x = p\omega$ as

$$Z = e^{i\omega T} = e^{i2d\sqrt{\omega^2/v^2 - k_x^2}} \ . \qquad (2)$$

If d and R are both constant, then equation (1) can be inverted to apply deghosting straightforwardly in the F-K domain or tau-p domain. When d and/or R vary spatially, then we instead use a method based on wavefield extrapolation, which is analogous to the phase-shift migration methodology described by Gazdag and Sguazzero (1984) and formalized as Fourier Integral Operators by Margrave and Ferguson (1999).

Examples

We now demonstrate the application of MWD and deghosting on a dataset from offshore Eastern Canada. The data is from a 2-D line from North Flemish Pass, provided to us by Jebco Seismic (Canada) Company. The data were acquired in August, 1998, with shot and receiver spacing of 25m and 12.5m respectively, with maximum offset of 6100m. Over the length of the line (143km) the water depth varies from approximately 165m to 1200m.

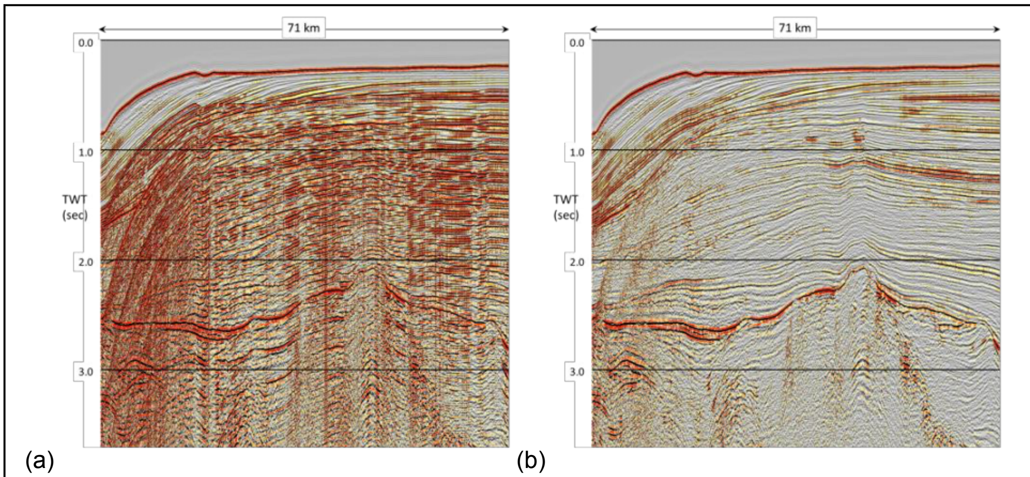

Figure 5. Stacked results of MWD on 2-D marine line from Flemish Pass showing: (a) input; (b) demultiple data.

Figure 5(a) shows the stack of the input data for approximately half of the line, predominantly in the shallower end. From approximately 0.5s to 2s several orders of pure water layer multiple are present, obscuring the primaries. Figure 5(b) shows the result of subtracting the predicted water-layer multiples. Furthermore peg-leg multiples generated by the strong reflector at approximately 2.5s are also well attenuated by the MWD.

Next we consider the impact of deghosting on these data. Figure 6 shows a stack from a different part of the same line without (a) and with (b) receiver deghosting application prior to MWD. The streamer was towed at a shallow depth of approximately 7m, leading to the pronounced notch near 100hz. Conventional processing would therefore be limited to a maximum frequency of approximately 90Hz.

In figure 7 the amplitude spectra for data in the window are shown. Deghosting has filled the notch to provide additional bandwidth at the high end up to about 120Hz, as well as enhancing the low frequency signal.

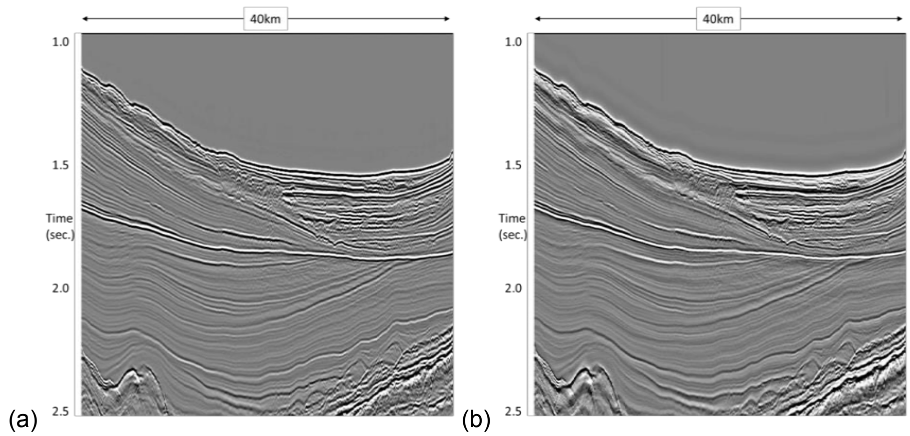

Figure 6. Stacked of East Coast marine data: (a) with no deghosting; (b) with receiver deghosting.

Figure 7. Amplitude spectra of stacks in figure 6.

Conclusions

While there are undoubtedly significant improvements in image quality resulting from new types of marine acquisition, application of new processing technology can also provide surprising uplift to older data.

We have particularly focussed on the two main steps in obtaining a *primary only* wavefield: demultiple and deghosting. We have made use of recent advances in the multiple prediction for shallow water-layer multiples, using an approach called MWD, to attack problematic multiples on a 2-D marine dataset. We stress the importance of separately handling shot-side and receiver-side peg-leg multiples in MWD, to properly deal with structure either in the water bottom or in the geology. For deghosting, a simple method using spectral division works well for a flat streamer towed under a relatively calm sea state, whereas for a streamer with noticable depth variability we make use of a wavefield extrapolation based approach.

Both demultiple and deghosting have been demonstrated on a line from Flemish Pass, providing what we believe is a cleaner, primary-only, image.

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