Comparing the interface and point scatterer methods for attenuating internal multiples: a study with synthetic data - Part II

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Summary

The relative strengths and limitations of the interface removal and point scatterer methods for attenuating internal multiples are compared using synthetic data examples. The interface method classifies internal multiples according to a subsurface interface which is responsible for the existence of the multiples. This method removes all orders of multiples for a given interface, one interface at a time starting with the shallowest reflector. In principle, exact earth model information is required down to and including the multiple generating interface. When the subsurface is sufficiently simple, the interface method can be effective.

The point scatterer method provides an alternative where reliable subsurface information is not available. Multiples are classified according the number of downward reflections a multiple has experienced in the subsurface irregardless of where those reflections occur. This method attenuates rather than eliminates all internal multiples of a given order for all subsurface reflectors, one order at a time. Unlike the interface method, no subsurface information is required. A numerical example is used to illustrate and compare these two methods.

Introduction

Free-surface and internal multiples are defined as multiply reflected events which experience two or more upward reflections in the subsurface. The former consists of all multiples that have experienced one or more reflections at the air-water or air-solid 'free' surface. The latter are events that have all of their downward reflection points below the free-surface.

There are currently two comprehensive methods for attenuating free-surface and internal multiples that are specifically designed to accommodate a multi-dimensional earth. The first approach is a free-surface and interface removal method that classifies multiples according to the shallowest reflector where the multiple has experienced a downward reflection (see, e.g., Berkhout (1982), Verschuur (1991), Berkhout and Verschuur (1997), and Verschuur and Berkhout (1997)). Multiples are removed by performing a transformation from seismic data in the presence of a multiple generating interface, to data without that interface.

The second approach derives from a task separated inverse scattering series and uses a free-surface and point scatterer model to describe and process free-surface and internal multiples respectively (see, e.g., Weglein et al. (1997), Carvalho et al. (1992), Araujo et al. (1994), and Matson and Weglein (1996)). Free-surface multiples are cataloged according to the number of times they have reflected from the free-surface; whereas internal multiples are classified in terms of the number of downward reflections they have experienced regardless of the location of these reflections in the subsurface .

In general, free-surface multiples are easier to remove than internal multiples because a single clearly defined and localized material property change, i.e., an extra boundary condition (the free-surface), can be viewed as bringing these multiples into existence. The interface or interfaces that generate internal multiples are often not as well known, making these multiples more difficult to attenuate.

The free-surface and interface removal and free-surface and point scatterer formulations both model the free-surface reflector as the generator of free-surface multiples. They differ, in their modeling of the source: the former method models the source as a vertical dipole in the water, whereas the latter models the sources as a monopole. To compensate for the actual monopole nature of the source, dipole data are approximated by removing the receiver ghost and leaving the source ghost intact. In the inverse scattering formulation, the presence of the obliquity factor reflects its modeling of the monopole source.

In principle, the dipole and monopole source formulations will predict different amplitudes for the multiples; the difference becomes more important with increasing offset and decreasing depth of reflectors. The two formulations also require a different wavelet for multiple removal, even at near offset. In practice, the differences between these two free-surface methods can be small and often are masked by other factors such as cable feathering, source and receiver array effects, and errors in deghosting. The adaptive subtraction process developed by Verschuur et al. (1992) is designed to compensate for errors whether they are due to acquisition imperfections or approximations in the theory. Hence, although conceptually and algorithmically distinct, in practice, the differences between the dipole and monopole formulations for free-surface multiples may be small.

While the free-surface and interface removal and free-surface and point scatterer approaches for attenuating free-surface multiples have definite similarities, the way in which they treat internal multiples is very different. In this paper, we review the underlying principles of the two methods for internal multiples and compare their different strengths and limitations. Synthetic data examples will be used to illustrate and compare the two methods.

For the purposes of this paper, we will refer to the two different internal multiple attenuation methods as the interface and point scatterer methods respectively. In our discussion of internal multiple attenuation, we assume that all free-surface multiples have been removed.

Interface Internal Multiple Attenuation

The interface removal method for internal multiples generalizes and extends the free-surface removal concept to subsurface reflectors.

The objective is to transform data to a form where the free-surface multiple removal concept can be applied to subsurface reflectors. This requires that the sources and receivers must be at or just below a known interface which is responsible for the existence of the multiples. Hence, the first step is to layer strip down to just below the interface of interest. A transformation must then be performed from data in the presence of the internal multiple generating interface, to data without that interface.

In principle, the layer stripping procedure requires exact information down to the interface of interest. Also, the reflective properties of the interface must be known. For simple interfaces such as the water bottom, this information can often be obtained reliably; however, as the depth and/or structural complexity increases, subsurface information becomes less reliable.

Another issue which is coupled to increasing complexity is how to properly formulate a transformation which removes the internal multiples. For free-surface multiples, this transformation is tractable due to the simplicity of the free-surface. For internal multiples, formulating this transformation for complex interfaces may not be so simple.

Both the complexity of the multiple removal transformation and the uncertainty of earth model information can have an adverse effect on the attenuation of internal multiples using the interface method. Where exact information is obtainable and the interfaces are relatively simple, this approach can be the method of choice due its simplicity and efficiency.

The practical methodology for applying the interface method and satisfying its requirements for a-priori information will be discussed in Part I of this two-part paper.

Inverse Scattering Internal Multiple A ttenuation

Inverse scattering provides an alternate way of attenuating internal multiples that has an entirely different attitude towards the classification of multiples and the need for a-priori information.

In contrast with the more traditional view of wave propagation, scattering theory has a perturbative view of forward modeling and seismic inversion. For example, in the forward scattering problem, a seismic event is modeled by summing an infinite perturbation series. In contrast with the way that the interface method describes event modeling, it takes an infinite series of terms to fully describe even the simplest seismic event (see, e.g., Matson (1996)).

The inverse scattering series has a similar perturbative attitude towards the processing of seismic data. This approach provides an avenue for formulating seismic processing in the absence of earth model information.

By describing the seismic inverse problem as a series of tasks and separating out the different portions of the inverse scattering series into these tasks, a subseries has been identified that attenuates internal multiples (Weglein et al. (1997)). Because the entire inverse scattering series can be formulated without any a-priori subsurface information, all of the tasks associated with inversion also retain this property. This is the reason that the internal multiple attenuation subseries does not demand any subsurface information.

In keeping with the perturbative character of the inverse scattering procedure, the series that attenuates internal multiples is a leading order approximation to a removal series. What is fortuitous is that this leading order approximation is remarkably effective at attenuating multiples; the timing for all predicted events is correct, even for converted phases (Coates and Weglein (1996)). In most cases, the amplitudes of predicted multiples differ from the actual by a small amount; hence, the multiples predicted for typical events are 80-95% of the amplitude of the actual multiple.

Unlike the interface method, the inverse scattering internal multiple attenuation procedure does not classify events according to an interface. Rather, it catalogs multiples according to the number of reflections an event experiences in the subsurface independent of the location of these reflectors.

Internal multiple attenuation is performed by using the original prestack data to calculate a series of terms each of which attenuates a different order of multiple. The equation for first order multiples in 2-D marine data is (Weglein et al. (1997) and Araujo et al. (1994))

$$b_{3IM}(k_g,k_s,q_g+q_s) = \frac{1}{(2\pi)^2}\int_{-\infty}^{\infty} dk_1 \int_{-\infty}^{\infty} dk_2$$
$$e^{-iq_1(z_g-z_s)}e^{iq_2(z_g-z_s)}\int_{-\infty}^{\infty} dz_1 b_1(k_g,k_1,z_1)e^{i(q_g+q_1)z_1}$$
$$\int_{-\infty}^{z_1-\epsilon} dz_2 b_1(k_1,k_2,z_2)e^{-i(q_1+q_2)z_2}$$
$$\int_{z_2+\epsilon}^{\infty} dz_3 b_1(k_2,k_s,z_3)e^{i(q_2+q_s)z_3}. \quad (1)$$

Here, k_g, k_s are the Fourier transform variables over geophone and source locations respectively, q_g and q_s are vertical wavenumbers given by $q_g = \sqrt{((\omega/c_0)^2 - k_g^2))}$ and $q_s = \sqrt{((\omega/c_0)^2 - k_s^2))}$ where c_0 is the water velocity and ω is the angular temporal frequency. The source and receiver depths are given by z_g and z_s respectively. The parameter ϵ ensures that z_1 is always greater than and not equal to z_2 and similarly for z_3. The quantity $b_1(k_g,k_1,z_1)$ is an uncollapsed migration which has been transformed to pseudo-depth using the water velocity (see, e.g., Weglein et al. (1997)).

To compute the multiple estimate, b_1 is input into an algorithm for equation (1) which then outputs the estimated internal multiples, b_{3IM}. When added to b_1, b_{3IM} suppresses all first order internal multiples. Note that the limits in the integrals over z_1, z_2, and z_3 limit the different portions of the data that are combined together. The limits $z_1 > z_2$ and $z_2 < z_3$ are the inverse series analog to the portion of the third term in the forward series that begins to create first order internal multiples.

The first term in the internal multiple attenuation series attenuates all first order internal multiples for all depths and times and alters higher order internal multiples. Hence, equation (1) predicts the correct phase of all internal multiples. Successively higher order terms in the series attenuate higher order internal multiples (see, e.g., Weglein et al. (1997) and Araujo et al. (1994)).

In practice, an adaptive subtraction process may improve the attenuative properties of the point scatterer method. This should be tempered with caution since internal multiples can often overlay primaries thus increasing the risk of removing primaries using minimum energy adaptive subtraction.

As we mentioned, this process, in principle, attenuates internal multiples as opposed to removing them. The most important aspect of multiple prediction and subtraction is correct timing. The ability to predict the correct travel time of all internal multiples and approximate their amplitude without any a-priori information is the greatest strength of the point scatterer method.

The computation time required is significantly greater than that required for free-surface multiples of the same order.

Synthetic Data example

Here we present a 2-D synthetic example from the first full implementation of the inverse scattering internal demultiple algorithm in the (k_g, k_s, z) domain. Previous examples on synthetic data were implemented using an approximate 2-D formulation in the $\tau - p$ domain (Coates and Weglein (1996)). As shown in Figure 1, the model consists of two planes with opposite dip.

Figure 2 contains 4 panels of data from left to right. The first panel is a shot record before internal multiple attenuation. The noise is due to the stair-step representation of dipping reflectors in finite difference modeling. The second panel contains the estimate of the first order internal multiples for this shot. This multiple estimate has been match-filtered to the input to account for the source wavelet. The third panel contains the input shot after direct subtraction of the match filtered multiples. The fourth panel is the input shot after adaptively subtracting the internal multiple estimate. Note that adaptive subtraction improves the attenuation of the multiples, particularly where the noise interferes with the multiple.

In principle, further terms in the multiple attenuation series are needed to suppress higher order internal multiples. However, the first term in the attenuation series correctly predicts the time of *all* internal multiples. A less expensive (but somewhat brute-force) approach is to use only the first order multiple estimate with adaptive subtraction to attenuate all the internal multiples. This process can also add benefit when the data are noisy, as is demonstrated in Figure 2.

Figure 3 shows the stack of the data before and after internal multiple attenuation using adaptive subtraction. The residuals are caused by edge effects due to the finite extent of the data.

Conclusions

The interface and point scatterer methods for attenuating internal multiples are compared using synthetic data examples to illustrate the relative strengths and weaknesses of the two methods.

Both methods operate by predicting and subtracting the internal multiples and both use information contained in the data to predict the multiples. However, the two methods are distinctly different in the way that multiples are cataloged and their requirements for a-priori information.

The interface method catalogs internal multiples according to a subsurface interface which is responsible for the existence of the multiples. The data are first layer stripped down to a multiple generating interface. The multiples are then removed by performing a transformation from data in the presence of the multiple generating interface, to data without that interface. This method removes all orders of internal multiples associated with a given interface, one interface at a time starting at the shallowest reflector. The requirements are, in principle, exact earth model information down to and including the interface of interest. When the internal multiple generating interfaces are sufficiently simple, the interface method can be effective.

The point scatterer method provides an alternative where reliable subsurface information is not available. Multiples are classified according the number of downward reflections a multiple has experienced in the subsurface regardless of where those reflections occur. This method attenuates all internal multiples of a given order for all subsurface reflectors, one order at a time. Unlike the interface method, no subsurface information is required.

These methods could complement each other: the choice depending on the type of multiple, the interface that generates it, and the availability of a-priori information.

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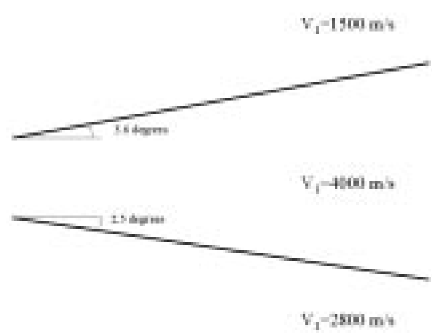

Fig. 1: Internal multiple model 1

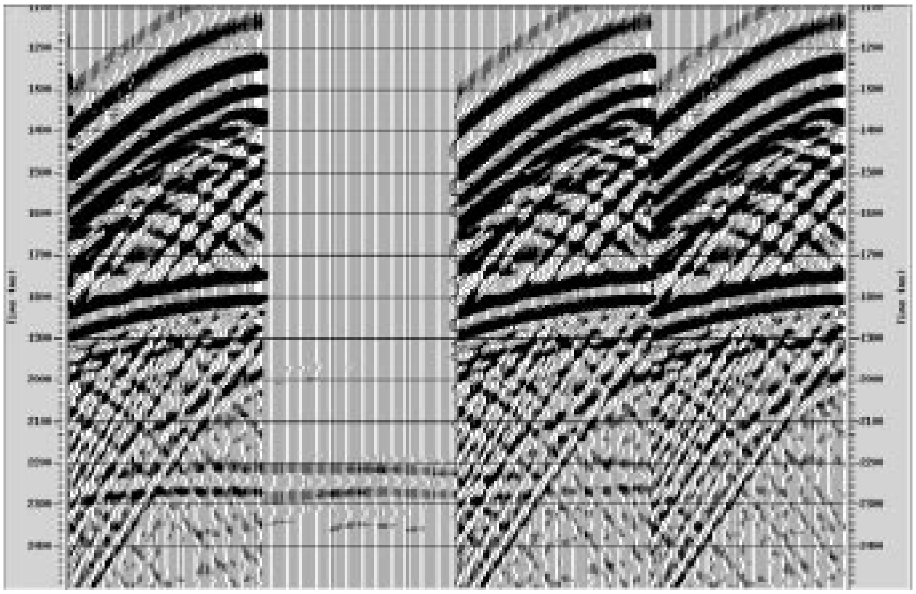

Fig. 2: Prestack data: input; estimated multiples; data after direct subtraction of multiples; data after adaptive subtraction of multiples

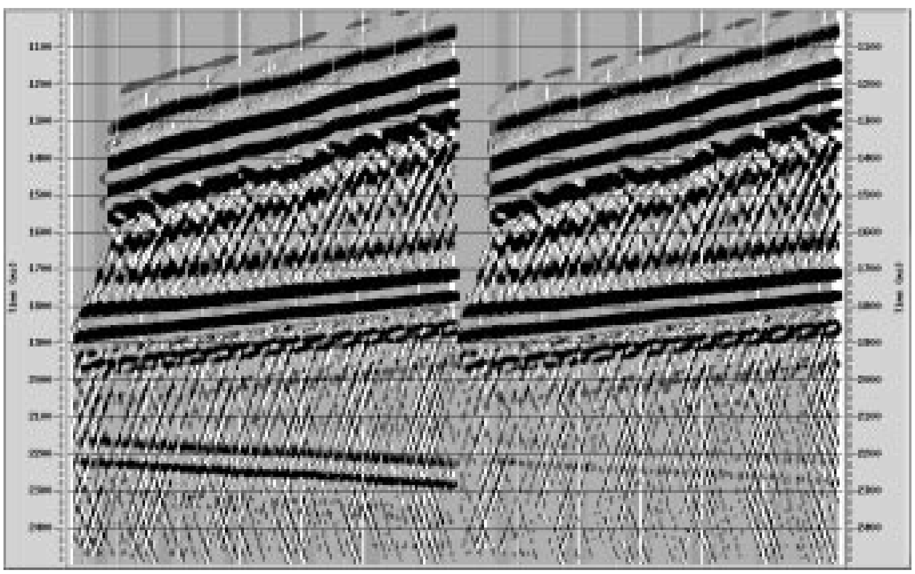

Fig. 3: Poststack data: before and after adaptive subtraction of estimated multiples