Inverse scattering internal multiple attenuation: results from complex synthetic and field data examples

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Summary

In this paper, we report the first application of the 2-D inverse scattering internal multiple attenuation algorithm to a full line of field data. We also present a synthetic data example with significant structural complexity to examine the performance of this method under challenging geologic circumstances.

Introduction

Seismic prospecting can be viewed as a process of extracting subsurface information from seismic measurements. Today's interpretation and inversion technologies demand sophisticated pre-stack amplitude-preserving processing technologies that are effective in complex geologic environments. For example, the advent and increased use AVO require advanced multiple suppression technology in seismically challenging areas where conventional 'tried and true' methods are no longer adequate.

A recent class of methods have been developed to fit the more stringent demands of inversion and amplitude processing. These methods classify multiples as either free-surface or internal multiples. Free-surface multiples contain one or more reflections from the air-water interface. Internal multiples have all of their downward reflections below the free-surface. Various realizations of free-surface multiple attenuation have been discussed in the literature (see e.g., Berkhout, 1982, Verschuur, 1991, Carvalho et al., 1992, Weglein et al., 1997). These methods are distinctive in that they are multi-dimensional, wave-theoretic, subsurface independent, and leave primaries and internal multiples intact. Hence they are specifically designed to meet the needs of pre-stack amplitude analysis in complex geology.

After removing the free-surface multiples, the stage is set for attenuating internal multiples. Two basic techniques have been formulated that specifically target internal multiples. The first is based on the feedback model developed at Delft University (Berkhout, 1982, Verschuur, 1991, Hadidi and Verschuur, 1997). The second is based on inverse scattering theory (see, e.g., Weglein et al., 1997 and Araujo et al., 1994). In a recent series of papers, the inverse scattering method and two realizations of the feedback method were compared using 2-D synthetic data examples (see Verschuur et al., 1998, Matson et al., 1998, Jakubowicz, 1998).

The feedback methods attenuate internal multiples related to a specific interface that is responsible for the generation of internal multiples i.e. the shallowest reflector where the internal multiple experiences a downward reflection. This is a top down process starting from the shallowest interface and requires an interpretive selection of the multiple generating reflector or a velocity model.

The inverse scattering method is not interface specific and attenuates all internal multiples of a given order at once without the need for interpretative intervention. (The order of the multiple refers to the number of changes in vertical propagation direction that it experiences in the subsurface.) In situations where the earth becomes complicated and interpretation becomes difficult, being able to attenuate multiples without the need for interpretive input is particularly important. The trade-off is an increase in computation time as compared to the feedback methods for a single interface.

In this paper, we further demonstrate the application of the inverse scattering method using a complex 2-D synthetic data example and field data examples.

Method

The development of the inverse scattering internal multiple attenuation method has been presented by previous authors (e.g., Weglein et al, 1997). For 2-D data acquired over a 2-D earth, the estimate of the first order internal multiples is given by

$$\boldsymbol{b}_{3IM}(\boldsymbol{k}_g,\boldsymbol{k}_s,\boldsymbol{q}_g+\boldsymbol{q}_s) = {}^{1}\!/_{(2\pi)^2}\int_{-\infty}^{+\infty}\boldsymbol{dk}_1\int_{-\infty}^{+\infty}\boldsymbol{dk}_2$$

$$\int_{-\infty}^{+\infty}\boldsymbol{dz}_1\boldsymbol{b}_1(\boldsymbol{k}_g,\boldsymbol{k}_1,z_1)\exp[\boldsymbol{i}z_1(\boldsymbol{q}_g+\boldsymbol{q}_1)+\boldsymbol{iq}_1\boldsymbol{z}_s]$$

$$\int_{-\infty}^{z_1-\varepsilon}\boldsymbol{dz}_2\boldsymbol{b}_1(\boldsymbol{k}_1,\boldsymbol{k}_2,z_2)\exp[-\boldsymbol{i}(\boldsymbol{q}_1+\boldsymbol{q}_2)\boldsymbol{z}_2-\boldsymbol{i}(\boldsymbol{q}_1\boldsymbol{z}_g+\boldsymbol{q}_2\boldsymbol{z}_s)]$$

$$\int_{z_2+\varepsilon}^{+\infty}\boldsymbol{dz}_3\boldsymbol{b}_1(\boldsymbol{k}_2,\boldsymbol{k}_s,z_3)\exp[-\boldsymbol{i}(\boldsymbol{q}_2+\boldsymbol{q}_3)z_3+\boldsymbol{iq}_2\boldsymbol{z}_g] \quad (1)$$

where $\boldsymbol{b_1}$ is an uncollapsed migration that has been transformed to pseudo depth $\boldsymbol{z}$ using the water velocity (see, e.g., Weglein et al, 1997). The quantities, $\boldsymbol{k_g}$, $\boldsymbol{k_s}$ are the

Fourier transform variables over geophone and source locations respectively, q_g and q_s are the vertical wavenumbers given by $q_g=\mathrm{sqrt}[(\omega/c_0)^2-k_g^2]$ and $q_s=\mathrm{sqrt}[(\omega/c_0)^2-k_s^2]$ where c_0 represents water velocity and ω represents angular temporal frequency. The source and receiver depths are given by z_s and z_g respectively. The parameter ε ensures that z_1 and z_3 are always greater than z_2. In practice, ε must be at least as long as the effective source wavelet. These data are input into an algorithm that computes b_3 in equation (1). The output from this algorithm are transformed back to time from pseudo-depth and then subtracted from the original input data.

An important pre-processing step is to remove the source wavelet from b_1 prior to computing the internal multiples. Unlike free-surface multiples, internal multiples are not computed one temporal frequency at a time. Consequently, the source wavelet contained in the data cannot be easily separated in equation (1) and estimated after the internal multiples are computed as is often done in the free-surface case (see, e.g., Verschuur, 1991. Ikelle et al. 1995). If the source wavelet is not removed prior to multiple estimation, it will become smeared across different frequencies and the estimated multiples will contain a distorted effective wavelet.

The wavelet from the free-surface multiple suppression algorithm can be used to deconvolve the source signature from the data provided the free-surface demultiple algorithm contains all the necessary factors (obliquity, deghosting, etc.).

Synthetic data example

We present a synthetic data example with significant structural complexity to illustrate and examine the effectiveness of the inverse scattering method under challenging circumstances. The model, shown in Figure 1, contains a large faulted anticline in a marine environment. From top to bottom, the model consists of five reflectors: water bottom, top of salt, base of salt, and two target reflectors below the salt.

The synthetic data were computed using a finite difference algorithm and consist of 101 sources recorded by 61 receivers. The source and receiver intervals are both 30 m. The free-surface has been turned off in the modeling code so that the internal multiples can be dealt with exclusively.

On the left panel in Figure 2, we show a stack of these data prior to internal multiple attenuation. The primary reflections are labeled using black arrows and the internal multiples are labeled with white arrows. The internal multiples can easily be mistaken for primaries - the algorithm is never confused. In the middle panel, we show the stack of the estimated internal multiples, and on the right, the stack of the input data after using a mild adaptive subtraction to remove the internal multiples pre-stack. It is important to realize that no a-priori subsurface information, identification, picking, or muting of any kind is required to attenuate all the internal multiples in this section. Amazingly, this method attenuates multiples that originate from within a salt body, without having to know anything about the salt!

Field data example

In this example, we show the first application of the 2-D inverse scattering internal multiple attenuation method to a full line of field data. The data set is from the Mississippi Canyon area in the Gulf of Mexico and was used for the Multiple Attenuation Workshop at the 1997 SEG meeting in Dallas. Since these data were acquired in deep water, the free-surface multiples arrive late in time. This allows us to deal with just the primaries and internal multiples that arrive before the first free-surface multiple.

We applied the free-surface multiple attenuation algorithm to these data to both attenuate the free-surface multiples and to estimate and ultimately remove the source wavelet. A stack before free-surface multiple attenuation is shown on the left hand side of Figure 3. On the right hand side, we show a stack after free-surface multiple attenuation and source wavelet deconvolution. As is evident from the repeated top-of-salt reflections, these data contain a source wavelet that rings. This can also be seen in Figure 4 which shows the average wavelet derived from the free-surface multiple attenuation algorithm.

The pre-processed data were input into the internal multiple attenuation algorithm and the estimated multiples were removed from the input data using a mild adaptive subtraction. In Figure 5, we show a common offset gather from a section of the input data, the estimated multiples, and the data after subtraction. The offset shown is 425 m and the CDP range is marked by the black box in Figure 3. The main multiple that is attenuated originates from a top-salt –> water-bottom –> top-salt reflection and arrives at the same time as the base of salt event. Although weak compared to the base of salt event in this example, these multiples are significant compared to the primary reflections beneath the salt. This presents a significant source of noise in situations where the internal multiples arrive below the salt.

Conclusions

The first results of applying the 2-D internal multiple attenuation algorithm to a full line of field data were presented and analyzed. The encouraging results from the internal multiple attenuation algorithm were run in a reasonable time frame. We anticipate a 3-D version in the near future.

An important preprocessing step is to remove the free-surface multiples and the source wavelet from the data. The algorithm requires absolutely no subsurface information, event selection or interpretive input - all internal multiples are predicted and attenuated at once.

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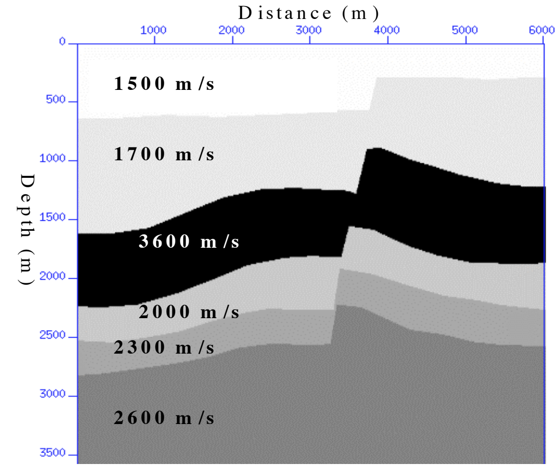

Figure 1: Synthetic model 1

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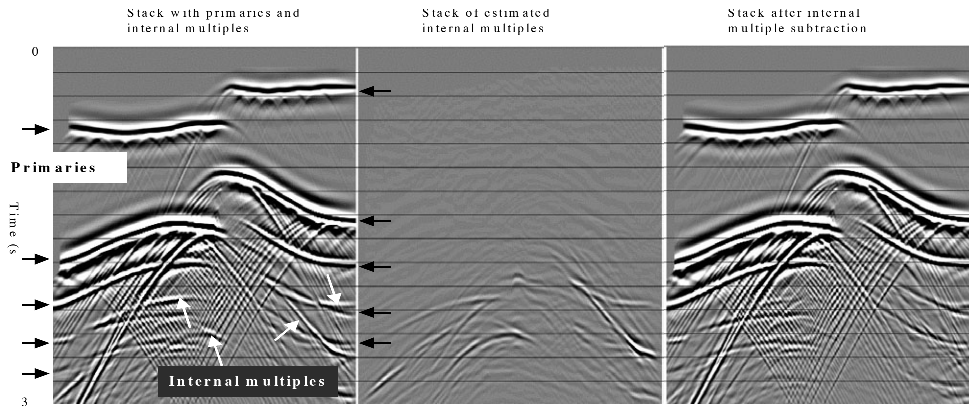

Figure 2: Synthetic model 1 stacks. Input data, internal mulitple estimate, input data after subtraction of internal multiples. Primaries are labelled with black arrows, internal multiples with white.

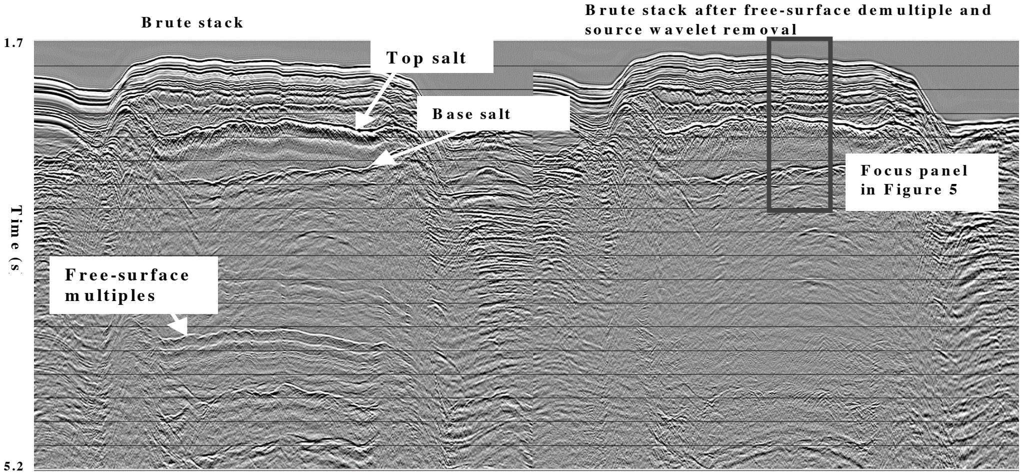

Figure 3: Mississippi Canyon field data example. Brute stack, brute stack after free-surface multiple attenuation and source wavelet removal.

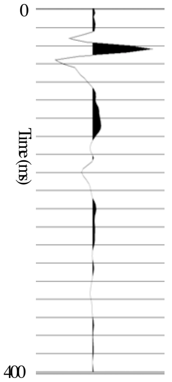

Figure 4: Average source wavelet

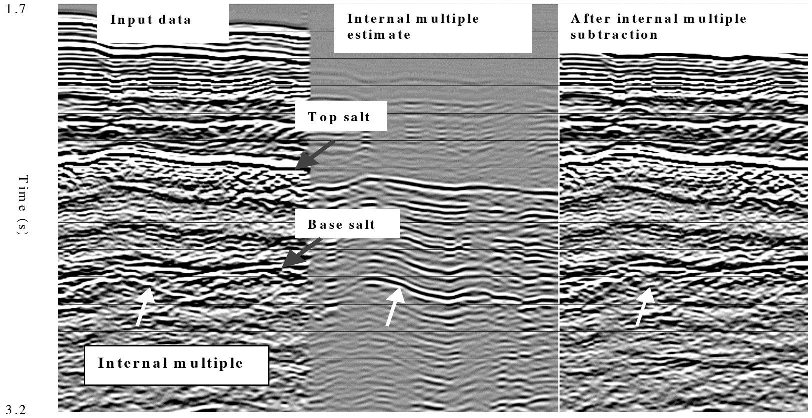

Figure 5: Common offset gathers: Input data, internal multiple estimate, input data after adaptive subtraction of internal multiples.