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Time domain internal multiple prediction on synthetic and field vertical seismic profile data

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Summary

Internal multiple prediction remains an important challenge for seismic imaging, inversion, and processing techniques. The inverse scattering approach presented by Weglein et al. (1997) remains the pinnacle of internal multiple attenuation technologies. Their method provides promising results on synthetic, and marine datasets, however, the application to land data remains a prevalent challenge for reasons outlined by Luo et al. (2011). Vertical seismic profiles (VSP) offer a unique dataset for exploring inverse scattering internal multiple attenutation methods for reasons outlined in this paper. We apply a work flow to predict internal multiples from both a zero offset synthetic and land VSP data according to the methods presented by Weglein et al. (1997) and Innanen (2015).

Introduction

The inverse scattering series approach remains the apex of internal multiple attenuation technologies. Originally presented by Weglein et al., (1997) their method has proven successful on both synthetic and marine datasets. Major complications in seismic acquisition on land, such as poor coupling, thinly bedded multiple generators, and noise (Luo et al., 2011) make it difficult to properly predict internal multiples on land. It is problematic that land internal multiples are the very multiples that are the most desirable to remove. Interpretation and inversion on land data has increasingly become more reliant on subtle features that can become masked by internal multiples.

The backbone of the inverse scattering approach relies on the fact that every internal multiple is a combination of sub-event primaries and multiples. In fact, it can be shown that every first order internal multiple is a combination of three sub-event primaries that obey a deeper-shallower-deeper relationship. The algorithm searches through the data for subevents obeying the deeper-shallower-deeper relationship and then predicts the traveltime of the related multiple by summing the traveltimes of the two deeper events and subtracting the traveltime of the shallower event. The original method searched for events in the wavenumber-psuedodepth domain, however, current research has evaluated the algorithm in other data domains to investigate if an optimal domain exists. One domain that has shown promise is that of the time domain (Innanen, 2015).

In the presence of horizontally layered geology, each trace of a zero offset VSP is a 1D seismic wavefield response, meaning that zero offset VSP are well suited for the application of 1D internal multiple prediction algorithms; the upgoing wavefield component being of particular interest. The prediction algorithm indiscriminately combines any sub-event obeying a deeper-shallower-deeper relationship, meaning that events such as noise, free surface multiples, and direct arrivals will be combined to erroneously predict artifacts that appear as multiple predictions. It is, therefore, important to prepare our data for prediction by removing free surface multiples and direct arrivals, and filtering as much noise as possible. However, the upgoing wavefield of a VSP is already free of the first two types of events, making it a well suited data set for internal multiple prediction. The high frequency nature of VSP data also places fewer constraints on the selection of epsilon. In addition, we may also ground truth our prediction by comparing it to the prediction generated by corridor stacking.

Theory and/or Method

The inverse scattering series internal multiple prediction algorithm presented by Weglein et al. (1997) takes the form:

$$b_3\left(k_g, k_s, \omega\right) = \frac{1}{(2\pi)^2} \iint\limits_{-\infty}^{\infty} dk_1 e^{-iq_1(\epsilon_g - \epsilon_s)} dk_2 e^{iq_2(\epsilon_g - \epsilon_s)} \times \varphi, \tag{1}$$

where

$$\varphi\left(k_g, k_1, k_2, k_s \middle| \epsilon\right) = \int\limits_{-\infty}^{-\infty} dz\, e^{i(q_g + q_s)z} b_1\left(k_g, k_s, z\right) \int\limits_{-\infty}^{z-\epsilon} dz'\, e^{-i(-q_1 - q_2)z'} b_1\left(k_g, k_s, z'\right)$$

$$\times \int_{z'+\epsilon}^{\infty} dz''\, e^{i(q_2 + q_s)z''} b_1\left(k_g, k_s, z''\right) \tag{2}$$

When $k_g = k_s = 0$ equation (1) reduces to the 1D frequency domain algorithm.

$$IM_\omega = \int\limits_{-\infty}^{\infty} dz e^{i\frac{\omega}{c_0}z} b1(z) \int\limits_{-\infty}^{z-\epsilon} dz' e^{-i\frac{\omega}{c_0}z'} b1(z') \int\limits_{z'+\epsilon}^{\infty} dz'' e^{i\frac{\omega}{c_0}z''} b1(z'') \tag{3}$$

Equation (3) represents the 1D frequency domain internal multiple prediction algorithm, where the depth z is actually pseudo depth and is calculated as $z = \frac{c_0 t}{2}$. The reference velocity c_0 is taken to be the velocity in the near surface, near the geophones; for marine experiments this is the velocity of water. Epsilon is a parameter, setting the minimum distance two events must be separated in order to be combined.

Replacing $b_1(z)$ with $d(t)$ and $k_z z$ with ωt, equation (3) becomes,

$$IM_t = \int\limits_{-\infty}^{\infty} dt e^{i\omega t} d(t) \int\limits_{-\infty}^{t-\epsilon} dt' e^{-i\omega t'} d(t') \int\limits_{t'+\epsilon}^{\infty} dt'' e^{i\omega t''} d(t'') \tag{4}$$

The product of the first and third integrals of equation (4) can be recognized as the product of two modified Fourier transforms over t and t''; therefore, this product represents a modified convolution. The second, integral being time reversed, represents a correlation; therefore, equation (4) represents the product of a modified convolution and a correlation, equation (4) then becomes,

$$IM_t = \int_{-\infty}^{\infty} dt'\, s(t' - t) \int_{\alpha(t,t')}^{\beta(t)} dt''\, s(t' - t'') s(t'') \tag{5}$$

where,

$$\alpha(t,t') = t' - (t - \epsilon)$$

$$\beta(t) = t - \epsilon \tag{6}$$

Equation (5) is the 1D time domain prediction formula derived by Innanen (2015), equation (6) represents the limits of integration that forces the deeper-shallower-deeper. Due to the fact that every trace of a zero offset VSP is a 1D wavefield response, the above algorithm can be readily applied to VSP data.

Examples

We start by applying the algorithm of (5) to a synthetic VSP data set created by acoustic finite difference modelling. The raw VSP is processed for the upgoing wavefield by first break picking, flattening on the first breaks, application of a median filter, and then subtraction of the downgoing wavefield from the total wavefield. The upgoing wavefield of a zero offset VSP theoretically should be free of direct arrivals, ghosts, and free surface multiples, thus providing a good candidate dataset for multiple prediction.

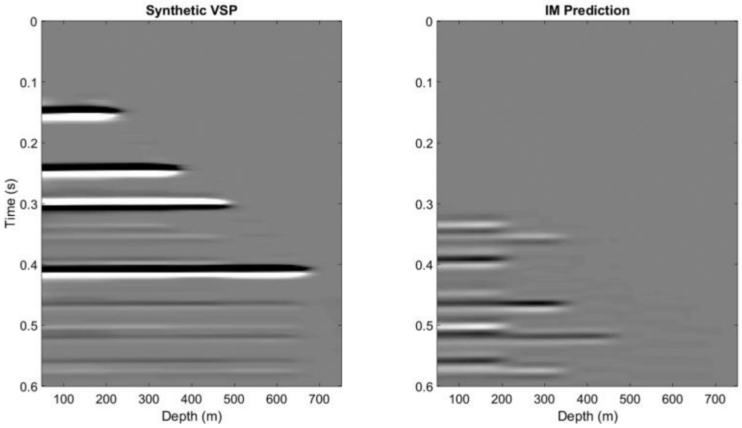

FIG 1. Synthetic VSP generated by acoustic finite difference (left), resulting prediction using time domain algorithm (right).

It can be seen that the multiples of figure 1 are accurately predicted, while the energy of the four primaries remains unaffected, thus we can say that the multiples have been correctly predicted. While the multiples have been accurarely predicted in time, they have not been predicted to their full lateral extent. The way in which VSP data is acquired means that once the tool string crosses an interface, that interface no longer produces a response in our data. The implications of this for multiple prediction is that we cease to be able to predict multiples laterally, this is due to the fact the algorithm no longer has the constituent events necessary to predict that given multiple. We propose creating zero offset sections by laterally extending these events in order to improve our ability to predict these multiples, figure (2) shows the results of this.

We then apply this methodology to a land zero offset VSP. Figure (3) shows on the left the filtered, processed data set (a), the predicion from the VSP (b), the zero offset section (c), the prediction from the zero offset section (d), and the difference section (e). While the prediction is quite noisy some bona fide multiple have been predicted, especially between 0.6-0.7 seconds and 0.8-0.9 seconds. Both of these regions represent times that are combinations of the most prominent primaries, and stong multiple energy has been predicted here, indicating that these are true multiples. It is encouraging to note that the difference section shows a strong increase in our prediction in these two regions when the prediction is based on a zero offset section.

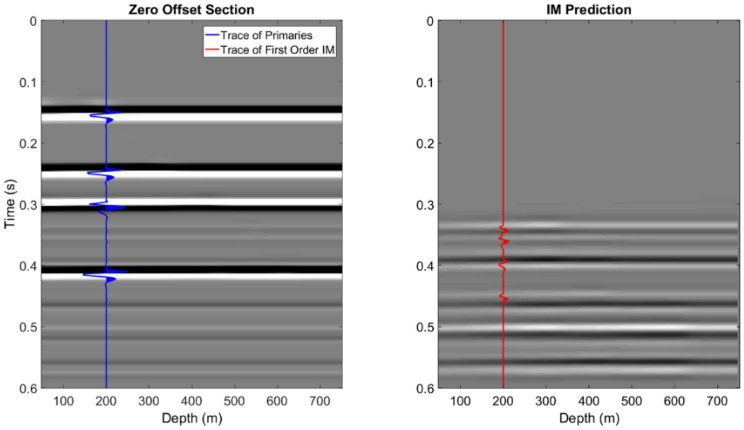

FIG 2. Synthetic zero offset section (left), resulting prediction using time domain algorithm (right).

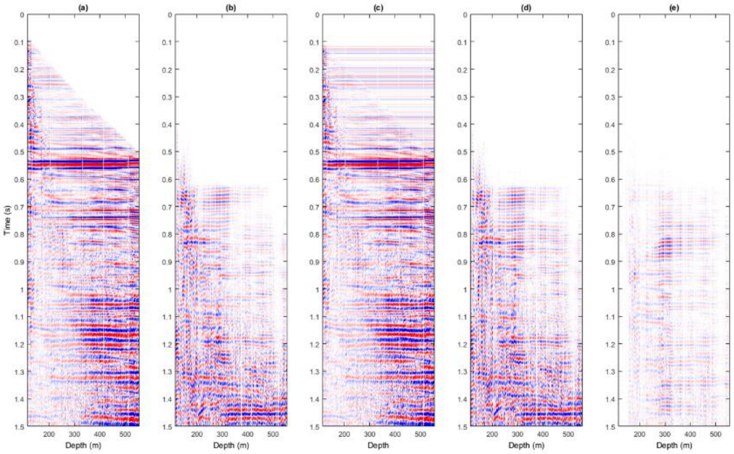

FIG 3. VSP data (a), internal multiple prediction from VSP (b), zero offset section (c), internal multiple prediction from zero offset section (d), difference section (e).

Conclusions

We discuss a fully data driven method for predicting internal multiples from VSP data which is based on the inverse scattering series. Innanen (2015) presented a 1D time domain version of this algorithm, which fortunately for us is well suited for application to VSP data sets. We show that this algorithm provides very clean and accurate predictions on synthetic data. The method of collection for VSP data means that events terminate once the tool has passed the generating interface, leading to an inabilty to predict multiples to their full lateral extent. By laterally extending events we have shown an increase in our ability to predict multiples in depth. Applying this methodology to land VSP data showed promissing results and an enhanced prediction in expected multiple regions after conversion of the data to a zero offset section.

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