Internal multiple attenuation based on inverse scattering: theoretical review and implementation in synthetic data

Melissa Hernandez and Kris Innanen

ABSTRACT

Multiple reflections represent a serious problem in the field of seismic processing. Multiple events can be mistaken for primary reflections, and may distort primary events and obscure the task of interpretation. In this work we will focus in the suppression of internal multiples and we will illustrate how the inverse scattering internal multiple algorithm introduced by Weglein and Araujo in 1994, is capable to attenuate internal multiples without any a priori information about the medium through which the waves propagate. One of the advantages of this method over other methods is its ability in principle to suppress multiples that interfere with primaries without attenuating the primaries themselves. We consider the version of the algorithm for 1D normal incidence case. This algorithm predicts internal multiples from other events in the data by performing a convolution and a crosscorrelation of data. In this paper we review the algorithm in theory, discuss intuitively how it works, and examine the numerical behaviour of the algorithm in synthetic data. In particular, the role and importance of the algorithm parameter ϵ is emphasized. The findings of this work are put to use in prediction of internal multiples in physical model data (Hernandez et al., 2011).

INTRODUCTION

Primary reflections are reflected only once at a certain subsurface interface before they arrive at the receivers. These primary reflections provide us with important information about the subsurface, such as velocities, density, geological structures, etc. Seismic imaging techniques are developed based on primary reflections. However, in addition to primary reflections, interfaces with a strong impedance contrast generate seismic multiples. Multiple reflections often interfere destructively with primary reflections and lead to poor seismic images.

Free-surface and internal multiples are defined as multiple reflected events that 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-earth or air-water boundary. The latter are events that have all of their downward reflection points below the free-surface (Cao, 2006).

Although these multiple reflections have been studied extensively, they continue to be a serious problem in the field of seismic processing. Multiple events can be mistaken for primary reflections, and may distort primary events and obscure the task of interpretation.

Multiple attenuation methods fall into three main categories. The first conventional approach is based on deconvolution. These methods use the periodicity of multiples for suppression and are useful in suppressing short-period free-surface multiples generated at shallow reflectors. The second category involves the use of filtering techniques, which take advantage of the different moveout of multiple reflections compared to primary reflections at the same time position. Wave equation methods are the third group. These use recorded data to predict multiples by procedures of wave extrapolation and/or inversion. These wavefield methods obtain multiple-free data by subtracting the predicted multiples and can suppress all multiples generated by any complex system of reflectors (Xiao et al., 2003).

Inverse-scattering techniques (Weglein et al., 2001) belong to the third group. They can suppress both free-surface multiples and internal multiples. Inverse-scattering series suppress one order multiples generated at all interfaces simultaneously (Ikelle et al. (1997);Weglein et al. (1997)).

In this work we examine the suppression of internal multiples and we will illustrate how the inverse scattering internal multiple algorithm is capable of attenuating internal multiples without any a priori information about the medium through which the waves propagate. Then, we will apply a simple 1D form of the algorithm to synthetic data.

INVERSE SCATTERING INTERNAL MULTIPLE THEORY

1D normal incidence internal multiple attenuation

The application of scattering theory into seismic processing has been studied since the last few decades, and has provided an alternative theoretical approach to understand, describe and represent seismic wave's behaviour. Basically, this theory relates a perturbation in the properties of a medium to the associated perturbation in the wave field. The first term in the internal multiple attenuation series for the 1D normal incidence case is Araujo et al. (1994):

$$b_{3IM}(k_z) = \int_{-\infty}^{\infty} dz_1' e^{k_z i z_1'} b_1(z_1') \int_{\infty}^{z_1'-\epsilon} dz_2' b_1(z_2') e^{-k_z i z_2'} \int_{z_2'+\epsilon}^{\infty} dz_3' b_1(z_3') e^{k_z i z_3'}, \tag{1}$$

The function $b_{3IM}(k_z)$ is a prediction of the internal multiple present in the data. It is in the k_z-domain, where k_z is the conjugate of pseudo-depth $(z = c_o t/2)$, hence the output can be straightforwardly transformed to the time domain. The $b_1(z)$ entries are the input data traces in pseudo-depth domain.

In order to obtain b_1, we begin with the measured surface data with no free-surface multiples, $D(x_g, x_s, t)$ where x_g and x_s are the receiver location, source location and time respectively. Then, a 3D Fourier Transform on these data is made to obtain $D(k_g, k_s, \omega)$. Here kg and ks are Fourier Transform variables over geophone and source locations respectively, q_g and q_s are vertical wavenumber. Subsequently the data is transform to vertical space, $D(k_g, k_s, q_g + q_s)$. The third is step is to transform the data to pseudo-depth, establishing that $k_z = q_g + q_s$. Then, the inverse Fourier Transform is performed to the data, $b_1 = (k_g, k_s, k_z)$ to $b_1 = (k_g, k_s, z)$. Finally we obtain the input $b_1 = (k_g, k_s, z)$ to compute the predicted multiple of equation 1. Once added to b_1, b_{3IM} attenuates all first order internal multiples (Weglein and Matson, 1998). In 1D, these steps reduce to a straight scaling of the time axis:$(t) \rightarrow D(z) = b_1(z)$, where $z = c_o t/2$.

Subevent Interpretation

This technique does not require subsurface information to achieve the suppression of internal multiples. Moreover, the internal multiple attenuation method can be explain using the concept of subevents. This algorithm predicts an internal multiple from interpreted subevents by performing a convolution and a crosscorrelation of prestack data. For example, the first order internal multiple in Figure 1 is composed of three subevents that satisfy the lower-higher-lower pseudo-depth condition. The parameter ϵ present in equation 1 ensures that z'_1 is always greater than and not equal to z'_3 and similarly for z'_3.

Analytic Example

To illustrate the basis of this method observe Figure 1. In Figure 1 a multiple is generated at source and received at the receiver; it can be seen as the convolution of three subevents. The temporal convolution and the correlation predicts the correct travel time of the multiple, and the spatial convolution predicts the proper offset, because the sum of the offsets of two subevents minus the offset of the third will equal the offset of the multiple (Weglein and Matson, 1998).

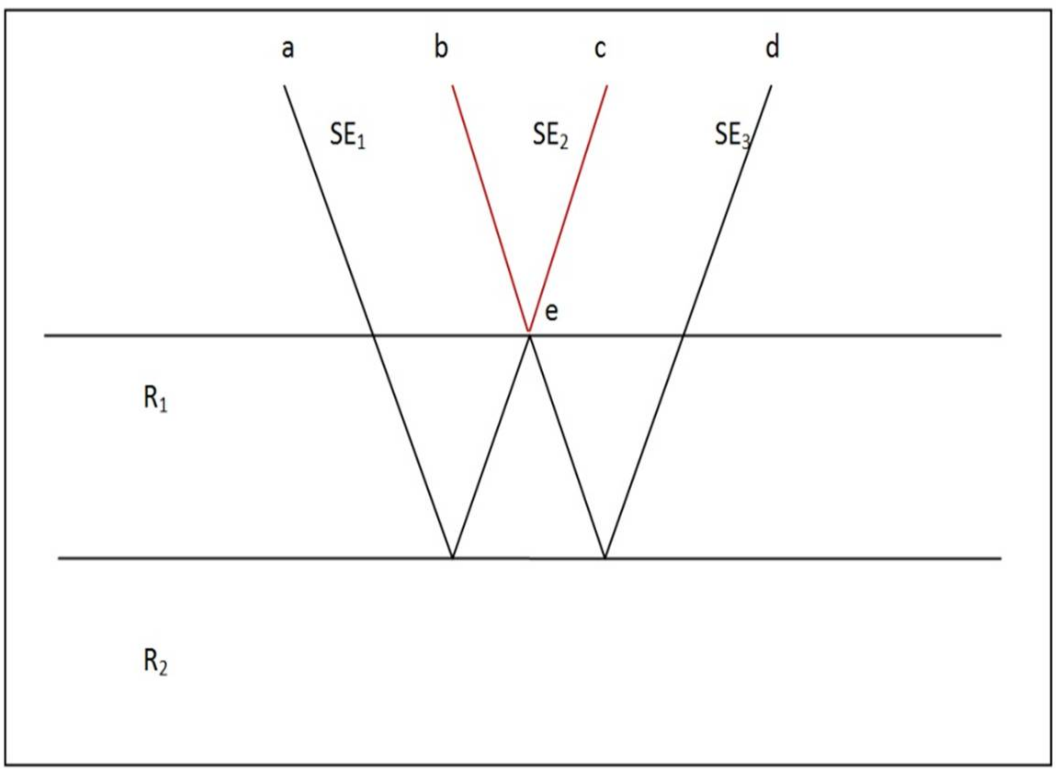

FIG. 1: Construction of internal multiple. The first subevent which a primary reflection that travel from point a, reflects from the second reflector, and is measured at c.The second subevent is a primary that propagates from b, reflects from the first interface at e, and then is measured at c. The third subevent propagates from b, reflects from the second interface and is measured at d. (Weglein and Matson, 1998)

Then, every event in the record can be thought of as a group of subevents. Convolving and correlating these subevents at a particular depths, the multiples are constructed. The input data to the algorithm is the multiple contaminated prestack data set. The output is a prestack data set that just contains the predicted multiples. Then by subtracting this second data set from the original input data, the multiples are attenuated or in the best case removed whilst the primaries remain undamaged (Matson et al., 1999).

Mathematically speaking we can describe in frequency the first subevent, a primary reflection, in Figure 1 as

$$SE_1(\omega) = T_1 R_2 T_1' e^{i\omega t_2}, \tag{2}$$

The second subevent, another primary, could be written in frequency as,

$$SE_2(\omega) = R_1 e^{i\omega t_1}, \tag{3}$$

And the third subevent is,

$$SE_3(\omega) = T_1 R_2 T_1' e^{i\omega t_2}, \tag{4}$$

Transforming these three subevent in pseudo-depth and substituting them in equation 1, we get equation 5. Also, since the three subevents are discrete localized events and satisfy the lower-higher-lower conditions, the integration limits could be extended to $\pm\infty$.

$$b_{3IM}(k_z) = \int_{-\infty}^{\infty} dz_1' e^{k_z i z_1'} SE_1(z_1') \int_{-\infty}^{\infty} dz_2' SE_2(z_2') e^{-k_z i z_2'} \int_{-\infty}^{\infty} dz_3' SE_3(z_3') e^{k_z i z_3'}, \tag{5}$$

Applying a Fourier Transform to the equation below can be written in the frequency domain as

$$b_{3IM}(\omega) = SE_1(\omega) SE_2(-\omega) SE_3(\omega), \tag{6}$$

Equation 6 describe the crosscorrelation of subevent 1 with subevent 2 followed by a convolution with subevent 3. Substituting the three subevents into equation 6 result

$$b_{3IM}(\omega) = T_1^2 R_2^2 R_1 T_1'^2 e^{i\omega(2t_2 - t_1)}, \tag{7}$$

The actual internal multiple in the frequency domain is written as

$$IM_I(\omega) = T_1 R_2 (-R_1) R_2 T_1' e^{i\omega(2t_2 - t_1)}, \tag{8}$$

Comparing equation 6 and 7 it is noticeable that the amplitude of the predicted multiple is off by a factor of $T_1 T_1'$. For typical earth velocities this error is very small and the predicted multiple gives a satisfactory degree of attenuation. This error could be due to that the leading order term in the internal multiple attenuation series does not properly take transmission effects into account and a reflection from above an interface is consider the negative of the reflection from above (Weglein and Matson, 1998).

Also, it is important to notice that the phase is correctly predicted, (Weglein and Matson, 1998).This algorithm achieves predict the proper travel time of the internal multiples based on the fact that the convolution of two arrivals will sum the travel time of those events, and the crosscorrelation will subtract their travel times.

Therefore, the travel time of subevent 1 and 3 will be summed while the travel time of subevent 2 will be subtracted. In fact, the portions of the three subevents that have the same travel path will cancel.

One of the most important characteristic of this algorithm is that it selects all the subevents that suit the lower-higher-lower relation through the integration limits of the equation 1 (Weglein and Matson, 1998).

INVERSE SCATTERING INTERNAL MULTIPLE ATTENUATION ALGORITHM

How the algorithm works

The inverse scattering internal multiple algorithm just needs the data itself as an input. The algorithm, before it predict the internal multiples makes a series of transformations of the data. First, to frequency domain and then to vertical wave number and finally to pseudo-depth. Once the data is transformed to pseudo-depth, the algorithm starts to search for possible multiples in the data. The subevents that the algorithm identifies as possible ray path of the internal multiples must satisfy the lower-higher-lower condition. The algorithm in fact treats the internal multiples as a combination of subevents. At this point the parameter epsilon is very important to consider, due to that this parameter limits the searching process. The value of epsilon is related to the width of the wavelet. The key to understand how this algorithm predict the internal multiples just with the data itself is to realize that the convolution of two subevents adds the times of these subevents and the crosscorrelation instead subtract the times. These subevents then construct at particular depth the internal multiple.

The output of the algorithm is a prestack data set that contains the predicted multiples. Then by subtracting this second data set from the original input data, the multiples are attenuated or in the best case removed whilst the primaries remain undamaged (Matson et al., 1999).

SYNTHETIC MODEL

Simple Synthetic Model

To start to work with the algorithm we generated a synthetic model. The model consists of three primary reflectors and two multiples.Table 1 resumes the information of this synthetic model.

One of the most important parameters to take in account of this method is the parameter epsilon ϵ. Several values of epsilon were tested, but the best fit was achieve setting epsilon equal to seven $(\epsilon = 7)$. A continuation we present the results obtained:

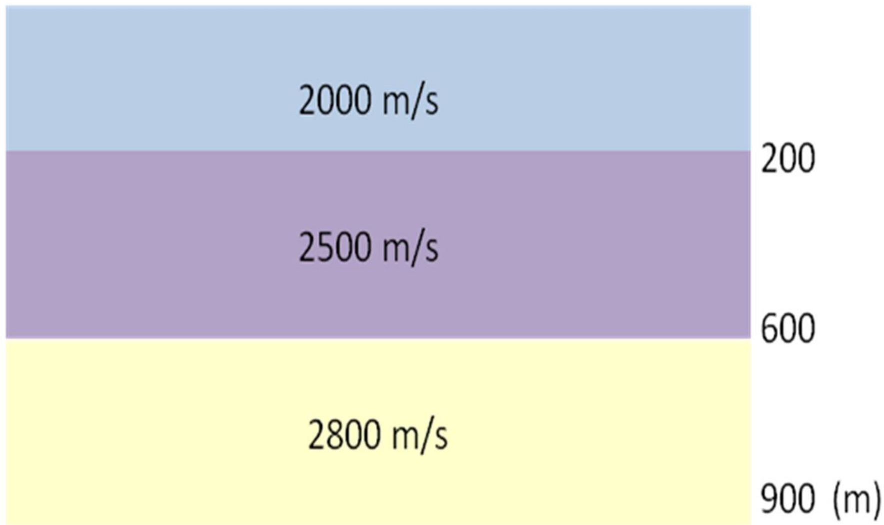

FIG. 2: Sketch of the synthetic model used

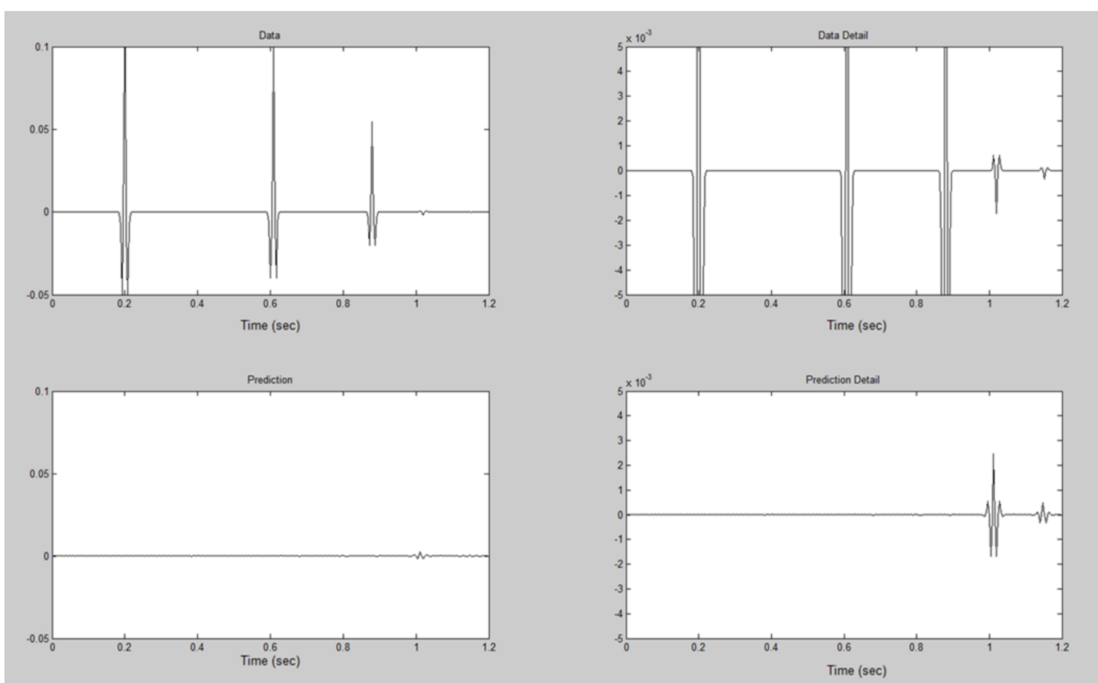

FIG. 3: Application of the 1D internal multiple attenuation algorithm for the synthetic model

PARAMETER	*VALUE*
Sample number	512
Interval Sample time	$3ms$
Velocity and depth of the first interface	$2000m/s\ at\ 200m$
Velocity and depth of the second interface	$2500m/s\ at\ 600m$
Velocity and depth of the third interface	$2800m/s\ at\ 900m$
Epsilon (ϵ)	7
Type of wavelet	Ricker
Wavelet central frequency	$60Hz$
Wave speed of the source/receiver medium	$1500m/s$

Table 1: Synthetic model parameters

PARAMETER TESTING

Effects of the Wavelet

In order to evaluate how sensitive is the algorithm to various parameters we made a series to tests, such as remove of the wavelet, i.e., the data no include effects of the wavelet. The results found do not show significant difference with the previous one, including wavelet. A continuation we present them.

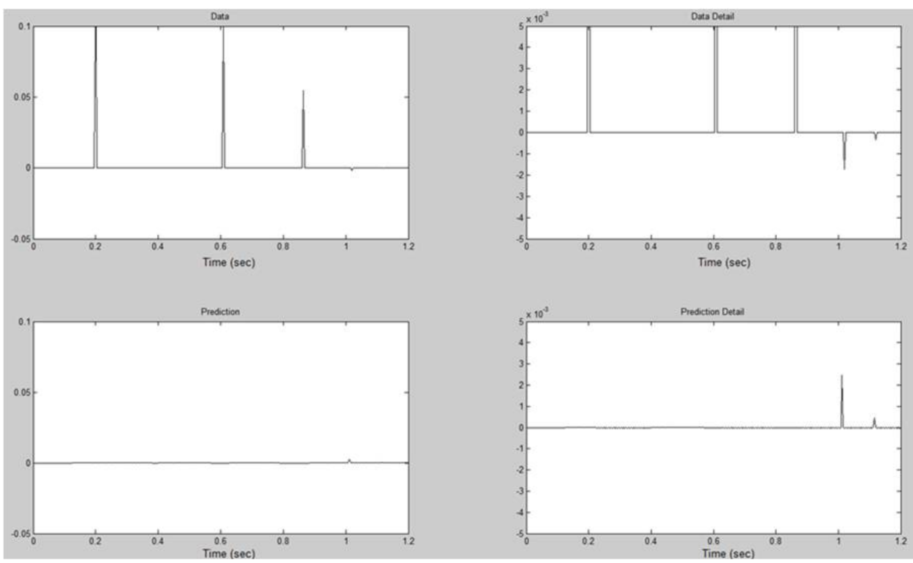

FIG. 4: Parameter testing: wavelet removal

Missing internal multiples in the input

The algorithm also predict or point out possible multiples even though when they are not included in the actual data. See figure below, Figure 5. This is an important result because through this we confirm that the algorithm effectively predicts multiples based on the combination of the primaries, that satisfy the lower-higher-lower condition. In the figure below we can notice that the algorithm predict to additional internal multiples that are not include in actual data, at deeper depths.

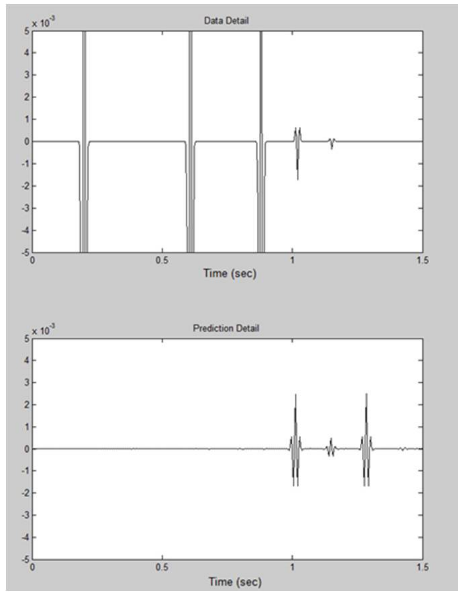

FIG. 5: Parameter testing: missing internal multiples in the input

Evaluation of epsilon extreme values

For smaller epsilon values, the algorithm affects the primaries. Therefore, an underestimation of epsilon significantlycould damage important information present in the data. An overestimation of the value of epsilon would not damage the data, but the output will not shows any internal multiples or other seismic events.

CONCLUSIONS

The principal objective of this work was to implement and test an inverse scattering internal multiple attenuation algorithm based on the work of Weglein and Araujo (1998). This work shows that the algorithm is capable to attenuate internal multiples without any a priori information about the medium through which the waves propagate. Based on the results found, several conclusions can be drawn: The output prediction depends strongly on the parameter epsilon. For the synthetic data the value of epsilon that performed the best prediction was 7. For smaller epsilon values, the algorithm affects the primaries. Therefore, an underestimation of ϵ could damage significantly important information present in the data. An overestimation of the value of epsilon would not damage the data, but the output will not show any internal multiples or other seismic events. For the synthetic model the algorithm works well, predicts multiples in the correct time and the amplitude is similar without any a priori information about the subsurface.

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