A clear example of using multiples to enhance and improve imaging; a comparison of two imaging conditions that are relevant to this analysis

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Abstract

In this paper, we use a 1D pre-stack example to examine the use of multiples to obtain an approximate image of an unrecorded primary following the imaging condition of space and time coincidence of up and down-going waves (referred to as Claerbout imaging condition II in Weglein, 2015). The result shows that, the image of an unrecorded primary (extracted from a recorded multiple) can be used to augment and enhance subsurface imaging from recorded primaries, when there is inadequate or insufficient acquisition of primaries. In addition, we carefully examine and analyze imaging results from two different and classic imaging conditions; (1) the predicted coincident source and receiver experiment at depth at time equals zero (referred to as Claerbout imaging condition III in Weglein, 2015). And (2) Claerbout imaging condition II. The result represents the advantages of Claerbout imaging condition III over Claerbout imaging condition II in terms of image definitiveness and consistency. However, a version of Claerbout imaging condition II has the advantage that it can use multiples to improve imaging result.

Introduction

In Claerbout imaging condition II (Claerbout, 1971), the source wavefield is forward propagated to the subsurface and the receiver wavefield is backward propagated to the subsurface; the imaging result is obtained by deconvolution, equation (1) (or cross-correlation, equation (2)) imaging condition (i.e., the space and time coincidence of up and down waves) (Claerbout, 1971, Whitmore et al., 2010):

$$I(\vec{x}) = \sum_{\vec{x}_s} \sum_{\omega} \frac{U(\vec{x}, \vec{x}_s; \omega)}{D(\vec{x}, \vec{x}_s; \omega)} \tag{1}$$

$$I(\vec{x}) = \sum_{\vec{x}_s} \sum_{\omega} D^{*}\left(\vec{x}, \vec{x}_s; \omega\right) U\left(\vec{x}, \vec{x}_s; \omega\right) \tag{2}$$

In equation (1) (or equation (2)), $D(\vec{x}, \overrightarrow{x_s}; \omega)$ and $U(\vec{x}, \overrightarrow{x_s}; \omega)$ represent down-going and up-going wavefields, respectively, and $*$ represents the complex conjugate.

Claerbout imaging II assumes that the data consists of primaries. Hence, multiples need to be removed prior to imaging (see e.g., Carvalho and Weglein, 1994; Verschuur et al., 1991; Araujo et al., 1994 and Weglein et al., 1997). Claerbout imaging II also requires a velocity model, and velocity analysis methods assume that multiples have been removed. However, while imaging requires only primaries, there are circumstances where the extant, sampling and acquisition of primaries is incomplete and less than adequate to achieve imaging objectives. Researchers (Berkhout and Verschuur, 1994; Guitton, 2002; Shan, 2003; Muijs, 2004; Whitmore et al., 2010, Lu et al, 2011, Valenciano et al., 2014) seeking methods to use multiples to extract an approximate image of an unrecorded primary, were influenced and inspired by the Claerbout imaging condition II (designed for imaging primaries) to consider the space and time coincidence of other useful purposes. The example below illustrates one way that extension was realized. For the purpose of using a multiple to find an approximate image of an unrecorded primary consider the field U (in equation (1) or (2)) as the source and receiver deghosted first-order multiple and the field D as the source deghosted, but the receiver ghost of the primary that is a recorded subevent of the multiple. That interpretation of equations (1) and (2), with that input D and U will produce an appropriate image of the unrecorded subevent of the multiple (see Weglein (2015) for more details).

Methods that seek to produce an approximate image of an unrecorded primary, from a multiple, require a velocity model. That in turn requires a step where multiples are first removed. Therefore, the recent interests in (and approaches for) using a multiple to provide an approximate primary depend on an effective removal of multiples before the method starts. Within that understanding, in this paper, we use a 1D pre-stack example to examine the image result of an unrecorded primary extracted from the multiples following Claerbout imaging condition II (i.e., equation 1), and compare that result to the image results obtained from the recorded primaries following the same Claerbout imaging condition II.

Furthermore, we will compare the image results of imaging primaries obtained by two different imaging conditions (i.e., Claerbout imaging condition II and Claerbout imaging condition III). Claerbout imaging condition III was first introduced by Claerbout (1971) for predicting the coincident source and receiver experiment at depth at time equals zero. The Claerbout imaging condition III predicts a physical experiment with both source and receiver at depth, allowing it to provide the imaging definitiveness that Claerbout imaging condition II cannot provide. On the other hand, the idea behind Claerbout imaging condition II inspired/influenced researchers to use multiples to provide an approximate image of an unrecorded primary. That is an advantage of Claerbout imaging condition II in comparison to Claerbout imaging condition III.

Pre-stack image enhancement by imaging an unrecorded primary extracted from a multiple

In this section, we provide a 1D pre-stack numerical example to examine the result of approximately imaging an unrecorded primary extracted from a recorded multiple. Multiples can be useful for extracting an unrecorded primary's image and thereby to enhance the subsurface image.

The test data are generated from a model which contains one horizontal reflector (see Figure 1). In imaging the recorded primary (Figure 2), the down-going wavefield that is being forward propagated is the source wavefield, and the up-going wavefield that is being backward propagated is the primary. In imaging the unrecorded primary (Figure 3), the down-going wavefield that is being forward propagated is the receiver-side ghost of the primary, and the up-going wavefield that is being backward propagated is the source-receiver side deghosted first-order free-surface multiple. Comparing the result in Figure 2 to the result in Figure 3, we note that the reflector is correctly imaged in both results; however, the image from the unrecorded primary plus the recorded primaries shows broader illumination compared with the image from imaging the recorded primaries only.

It is important to point out that, in obtaining the result of Figure 3 in this synthetic example, we purposefully chose the **receiver-side ghost of the primary** and **source-receiver side deghosted first-order free-surface multiple** as the down-going (D) and up-going (U) wavefields, respectively. Methods that seek to obtain an approximate image of an unrecorded primary require an effective up-down wavefield separation, which can be achieved by modern seismic acquisition technique (e.g., GeoStreamer or Over/Under cable). Notice that, among different combinations between the down and up going events, cross-talk artifacts can happen.

A 1D pre-stack example and the differences between Claerbout Imaging Conditions II and III

The Claerbout Imaging Condition III (i.e., the predicted coincident source and receiver experiment at depth, at time equals zero) is the definition of wave-equation migration. Claerbout Imaging Condition II is not equal to the Claerbout Imaging Condition III in anything beyond 1D normal incidence or zero-offset data.

In this section, we will show the images generated by Reverse Time Migration (Claerbout Imaging Condition II) and Stolt migration, equation (3) (Claerbout Imaging Condition III for one-way wave) for a single horizontal reflector.

$$I^{Stolt}(x,z) = \frac{1}{(2\pi)^3} \int d\omega \int dk_{sx}\, e^{-i(k_{sz}z + k_{sx}(x-x_s))} \int dk_{gx}\, e^{i(k_{gz}z + k_{gx}(x-x_g))} \iiint dx_g dx_s dt\, e^{i\omega t} D(x_g, x_s; t) \tag{3}$$

Figure 1 shows the one-reflector model we used for this test. Figure 4 shows the image generated by Reverse Time Migration with a single shot gather (one source); we observe that there is a blur on the image as well as some artifacts generated by the limited aperture. In practice, a sum over all sources is taken with the assumption that the blur and artifacts will go away. However, summing over all sources does not have a clear physical meaning and it is not guaranteed that all the blur and artifacts will go away. Figure 5 shows the image generated by Stolt migration with exactly the same data. We can observe the image is flat and with few artifacts. More importantly, every step in Stolt migration has a clear physical meaning. Thus we can readily obtain interpretable amplitude information, such as angle dependent reflection coefficient, from Stolt migration (see Zou et. al., 2015 for more detail).

Conclusion

Following Claerbout imaging condition II, multiples can be used to extract the image of unrecorded primaries to complement the subsurface imaging results in the case where the acquisition of primaries is inadequate. However, there still are artifacts (e.g., unwanted cross-talk) in the real applications using multiples to improve subsurface imaging. Therefore, this double-edged procedure needs to be judiciously applied in real applications. Weglein (2014) RARA showed several convincing PGS field data examples with considerable added value from using multiples to enhance imaging. The comparison of the imaging result of primaries following two different imaging conditions (Claerbout imaging condition II and III) demonstrates the superiority of Claerbout imaging condition III over Claerbout imaging condition II in terms of the definitiveness and consistency of the image. The Claerbout imaging condition II allowed/encouraged the consideration of the space and time coincidence idea for different up and down going wavefields (other than the original imaging concept was intended) an interpretation to provide added value for using multiples to approximate the image of an unrecorded primary. The latter advantage is not available in the more definitive Claerbout imaging condition III.

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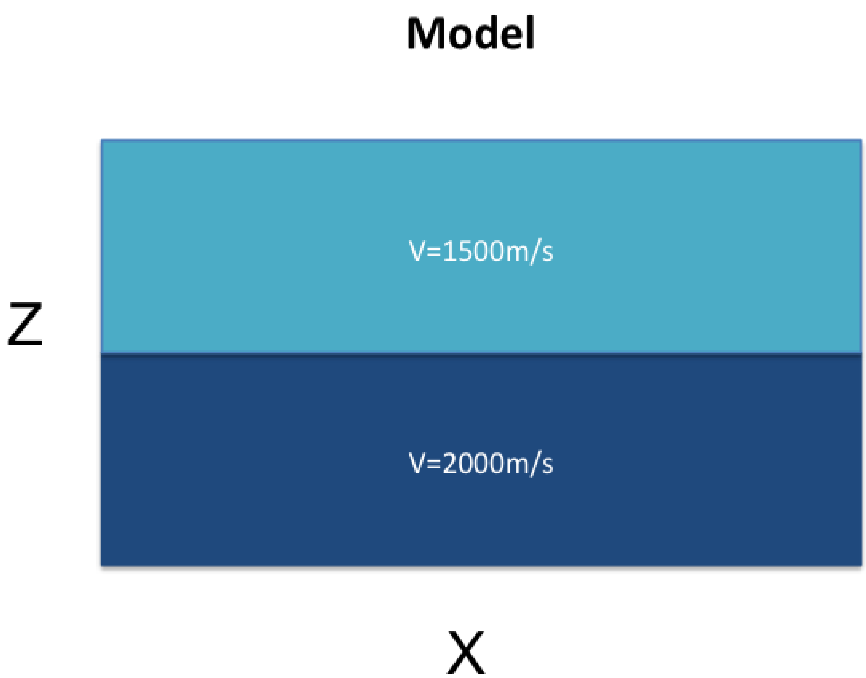


Figure 1, A one horizontal reflector test model.

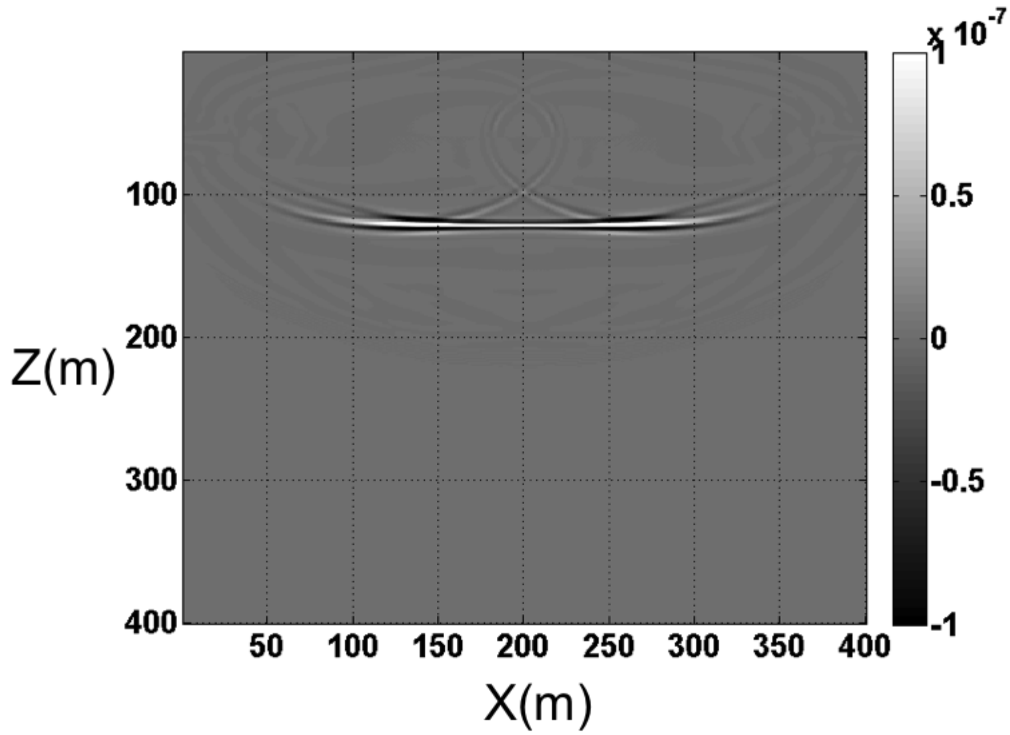


Figure 2, Imaging result by imaging a primary following Claerbout imaging condition II.

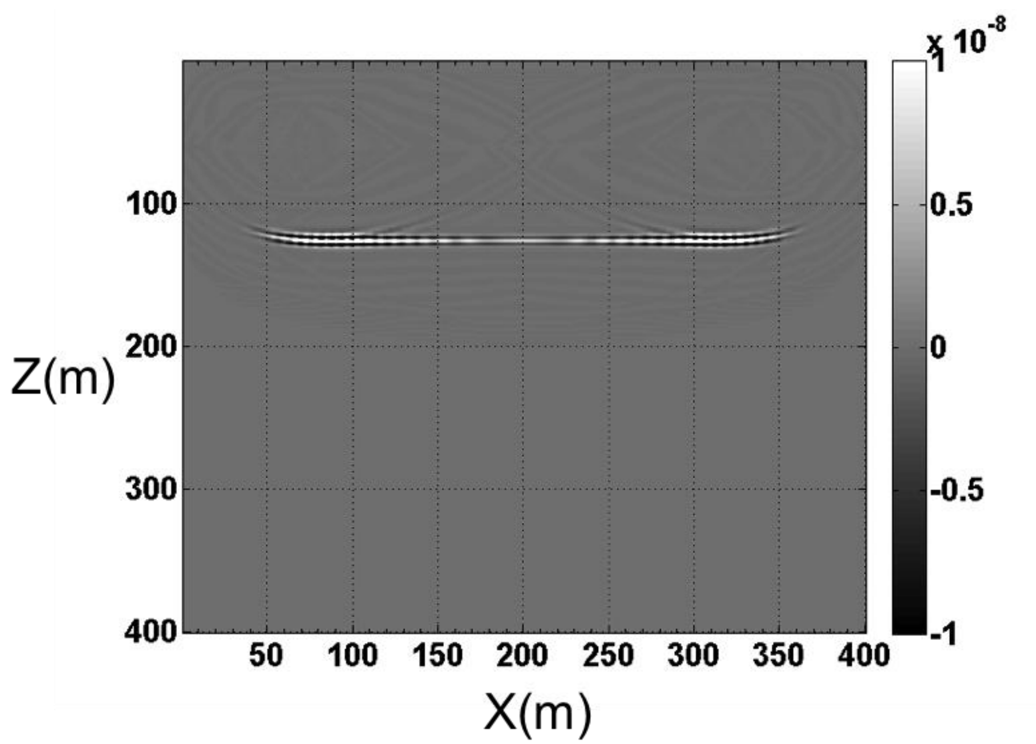
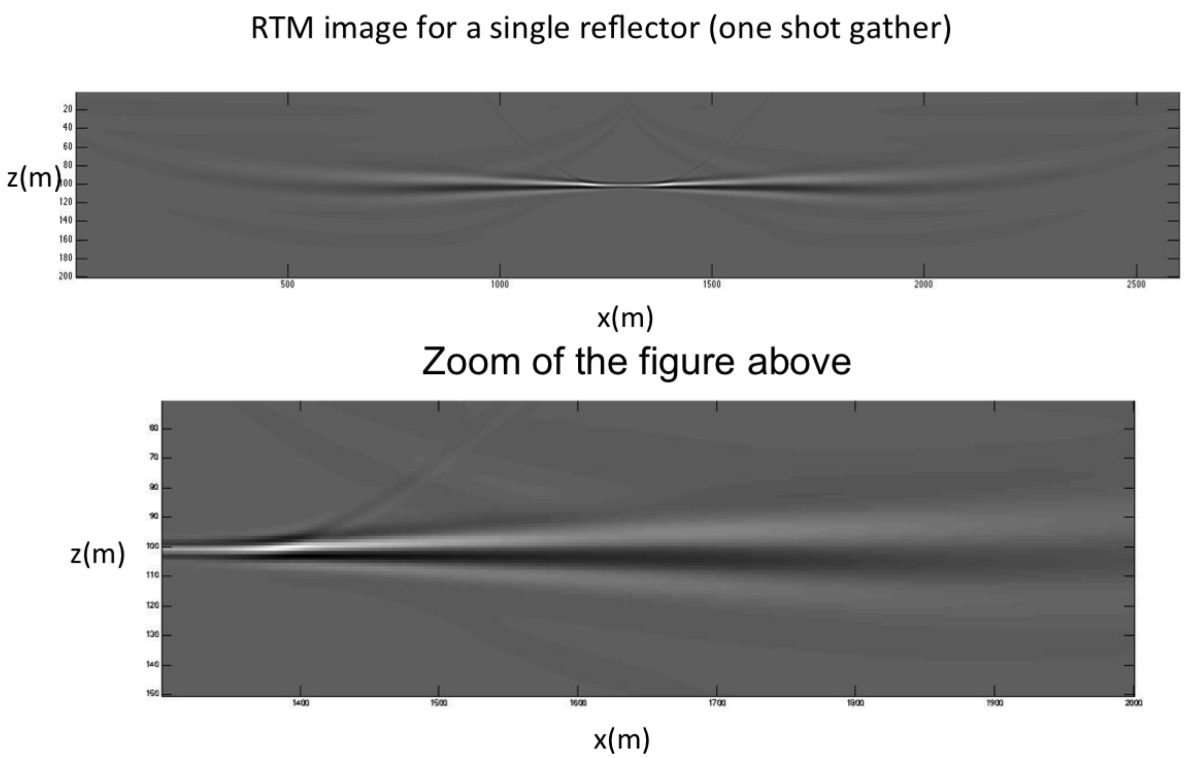


Figure 3, Imaging result by imaging an extracted primary from a first-order free-surface multiple following Claerbout imaging condition II



Figur 4, image result (one shot gather) following Claerbout imaging conidtion II

The figure below is zoom of the figure above.

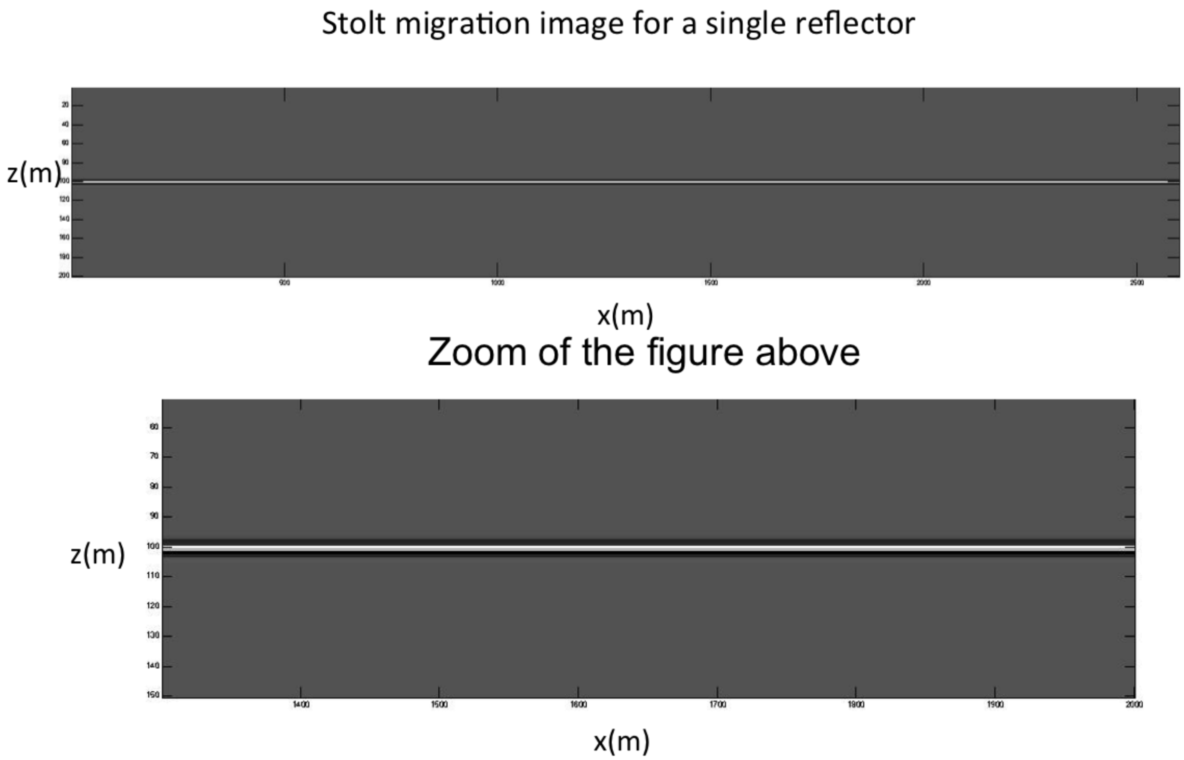


Figure 5, image result following Claerbout imaging conidtion III.

The figure below is zoom of the figure above.