Multi-virtual sources method in Marchenko imaging

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Summary

In recent years, Marchenko method has been applied in the migration imaging which is called Marchenko imaging. The Marchenko equation can retrieve the Green's function between the virtual source in subsurface and receivers at surface using the reflection responses measured at surface and the direct arrivals from the virtual source calculated through the background velocity field. By decomposing Marchenko equation, the Green's function can be splitted into upgoing and downgoing Green's functions. We are able to create an image by computing the cross-correlation function which is an integral of the convolution of upgoing Green's function with downgoing Green's function. The advantage of Marchenko imaging method is that an approximate background velocity is sufficient to create an accurate image. However, Marchenko method is a fully data-driven approach. For each image point, there is a need to calculate an approximate direct wave, which is very time consuming. In this paper, a method based on multi-virtual sources is proposed. The direct arrivals from multiple virtual sources are calculated at the same time, and then they are separated for each individual virtual source. In this way, the computational time can be significantly reduced depended on number of virtual sources being set and therefore efficiency is greatly improved.

Introduction

Marchenko equation forms a basis for 1D inverse scattering theory (Marchenko,1955). The Marchenko method was first introduced to the geophysical field by Borggini and Snieder (2012). The Marchenko equation can relate the reflection responses received at the surface to the Green's function from the virtual source in subsurface (Wapennar et al.,2014b). Subsequently, Broggini et al. (2012) and Wapenaar et al. (2013) extended the Marchenko equation into the two and three dimensions. From the reflection responses data, the upgoing and downgoing Green's functions from a certain virtual source point in the underground medium can be retrieved. The Green's functions can be used to create the image of target zone in the subsurface without the influence of multiple waves (Wapennar et al., 2014b). The Marchenko imaging method uses true upgoing and downgoing wavefields to image the target area. The image obtained is free of spurious events related to the internal multiples.

The Marchenko imaging method is a completely data-driven method. For each imaging point, there is a need to calculate approximate direct arrivals, which is very expensive. In this paper, we apply an idea of multiple virtual sources in this method. That is, instead computing direct arrivals from each individual imaging point (a virtual source location), we simulated direct arrivals from multiple virtual source locations simultaneously. The direct arrivals are separated for each virtual source. Depending on the number of imaging points taken into account, the multifold amount of computational time to simulate direct arrivals can be reduced. The results show that this new method can effectively improve the computational efficiency without affecting the imaging quality.

Theory and Method

In Marchenko imaging, Wapenaar et al. (2014) introduced focusing functions including upgoing (f^-) and downgoing (f^+) parts which are defined to relate the upgoing (G^-) and downgoing (G^+) Green's functions in the subsurface with the reflection response at surface (Wapenaar et al., 2014b):

$$G^+(x_F,x_S,t) = -\iint R(x_S,x,t-t')f_1^-(x,x_F,-t')dt'dx + f_1^+(x_S,x_F,-t) \quad (1)$$

$$G^-(x_F,x_S,t) = \iint R(x_S,x,t-t')f_1^+(x,x_F,t')dt'dx - f_1^-(x_S,x_F,t) \quad (2)$$

where R is the reflection response without surface multiple and deconvolved with the wavelet. Here, x is the observation point and t is the time, while x_F and x_S denote the focal point and the source location respectively.

There is no energy arrives before the direct arrival (t_d) according to causality principle (Wapenaar et al., 2014b). Therefore, the Green's functions $G^{\pm}(x_F,x_S,t)$ are zero when $t < t_d$ which leads to:

$$0 = -\iint R(x_S,x,t-t')f_1^-(x,x_F,-t')dt'dx + f_1^+(x_S,x_F,-t) \quad (3)$$

$$0 = \iint R(x_S,x,t-t')f_1^+(x,x_F,t')dt'dx - f_1^-(x_S,x_F,t) \quad (4)$$

This coupled system is called Marchenko equation. The downgoing focusing function is equal to the inverse of the transmission response of the medium (Wapenaar et al., 2014a) which leads to:

$$f_1^+(x,x_F,t) = T^{inv}(x_F,x,t) \quad (5)$$

10.1190/SEIM2018-18.1

This equation is used to derive an initial estimate for f_1^+, and T^{inv} can be interpreted as a direct arrival followed by scattering coda according to Van der Neut et al. (2015). Thus, the equation (5) can be rewritten as:

$$f_1^+(x, x_F, t) = T_d^{inv}(x_F, x, t) + M^+(x, x_F, t) \qquad (6)$$

where M^+ is the scattering coda following the direct arrival, similarly, it is zero when $t < -t_d$, T_d^{inv} is the direct arrival of T^{inv}. Wapennar et al. (2014) took the time reversal of the direct arrival $G_d(x, x_F, t)$ of Green's function as approximate T_d^{inv}:

$$f_1^+(x, x_F, t) \approx G_d(x, x_F, t) + M^+(x, x_F, t) \qquad (7)$$

We can get the estimate of the direct arrival $G_d(x, x_F, t)$ by performing a forward propagation with a background velocity field. The reflection response R and the estimated direct arrival G_d are sufficient to solve the scattering coda M^+ for estimating focusing functions $f_1^{\pm}$. The Marchenko equation is solved by the following equations (Wapenaar et al., 2014b):

$$M_k^+(x_S, x_F, -t) = \iint R(x_S, x, t-t') f_{1,k-1}^-(x, x_F, -t')\, dt'dx \qquad (8)$$

and

$$f_{1,k}^+(x_S, x_F, t) = G_d(x_S, x_F, -t) + M_k^+(x_S, x_F, t) \qquad (9)$$

and

$$f_{1,k}^-(x_S, x_F, t) = f_{1,0}^-(x_S, x_F, t) + \iint R(x_S, x, t-t') M_k^+(x, x_F, t')dt'dx \qquad (10)$$

with

$$f_{1,0}^-(x_S, x_F, t) = \iint R(x_S, x, t-t') G_d(x, x_F, -t')dt'dx \quad (11)$$

By substituting equation 9 and 10 into equation 1 and 2 respectively, one can obtain the Green's functions including upgoing part and downgoing part. The cross-correlation function for each imaging point can be computed as followed equation (Broggini et al.,2014):

$$\mathrm{C}(x_F, x_F, \mathrm{t}) = \int G^-(x_F, x, t) * G^+(x_F, x, -t)dx \qquad (12)$$

The value of $\mathrm{C}(x_F, x_F, \mathrm{t} = 0)$ is what we use to create image at x_F. All above are the definition of the iterative Marchenko scheme.

The Multi-virtual sources method that we have used in Marchenko imaging is described as followed. First, in the process of performing forward propagation to get direct arrivals, we set multiple virtual sources with a certain interval at the same depth in the background velocity field. Then, after the direct arrivals from the multiple points are obtained, we define the time-window to separate them out. The time-window is set along the event of direct arrival which can be tracked by its maximum amplitude or time-distance curve.

Examples

To verify the validity of the method, a simple model is used as shown in Figure 1. Figure 1 is a velocity model which is discretized into 2001×401 grids with intervals of 5m. There are 601 shots with intervals of 10m. Every shot has 201 receivers with intervals of 5m. The synthetic data is obtained using finite difference method. The record length is 2s with a 4ms sampling interval. One shot gather after direct arrival elimination is shown in Figure 2.

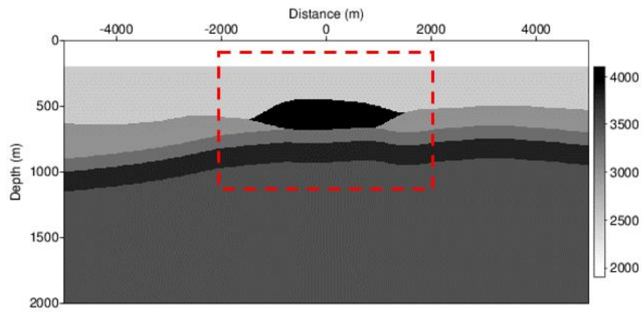

Fig 1. Velocity model

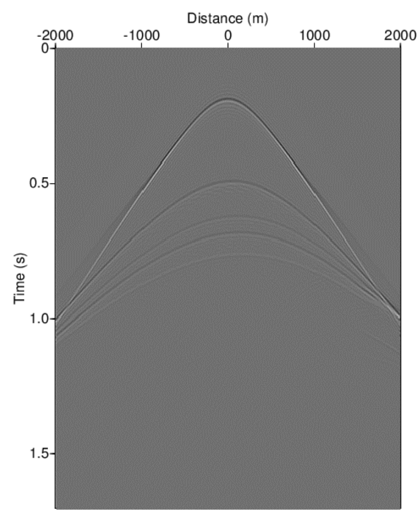

Fig 2. Reflection data observed at surface

We specify a target area to conduct imaging as shown in Figure 3 which is bounded by red dotted line in Figure 1. The Figure 3(a) is the velocity model of target area. Figure 3(b) is a smooth version of the velocity model. The Figure 4(a) shows the direct arrivals with four virtual sources placed in the smoothed velocity field with a certain interval at the same depth as shown in Figure 3(b). Figure 4(b) shows the direct arrival from one source which is separated from Figure 4(a) through a time-window defined by direct arrival's event. Even though the separated direct arrival is not very clean, it will hardly have an impact on imaging result as shown in Figure 5. The Figure 5(a) is the imaging result with one virtual source each time using the true velocity in Figure 3(a). While, Figure 5(b) shows the imaging result with one virtual source, and Figure 5(c) is the imaging result with four virtual sources, both of which adopts the smooth velocity in Figure 3(b).

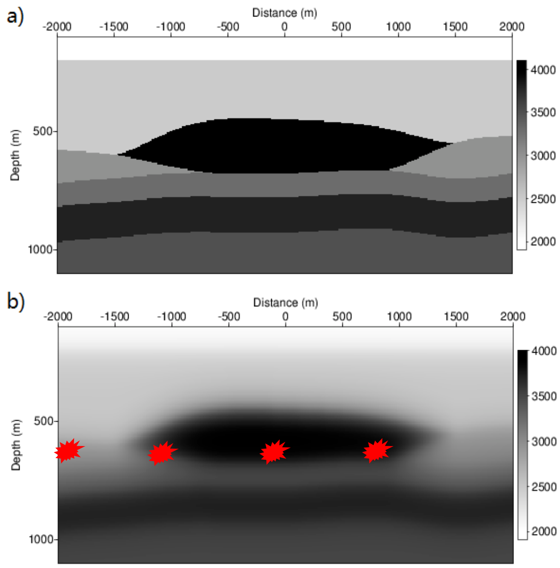

Fig 3. Target imaging area
a)true velocity; b) initial velocity

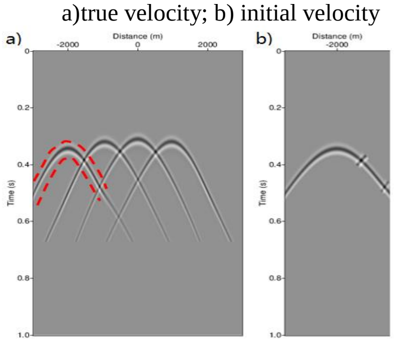

Fig 4. Direct arrival
a) direct arrivals with four virtual sources; b) direct arrival with one source separated from a) with a time-window

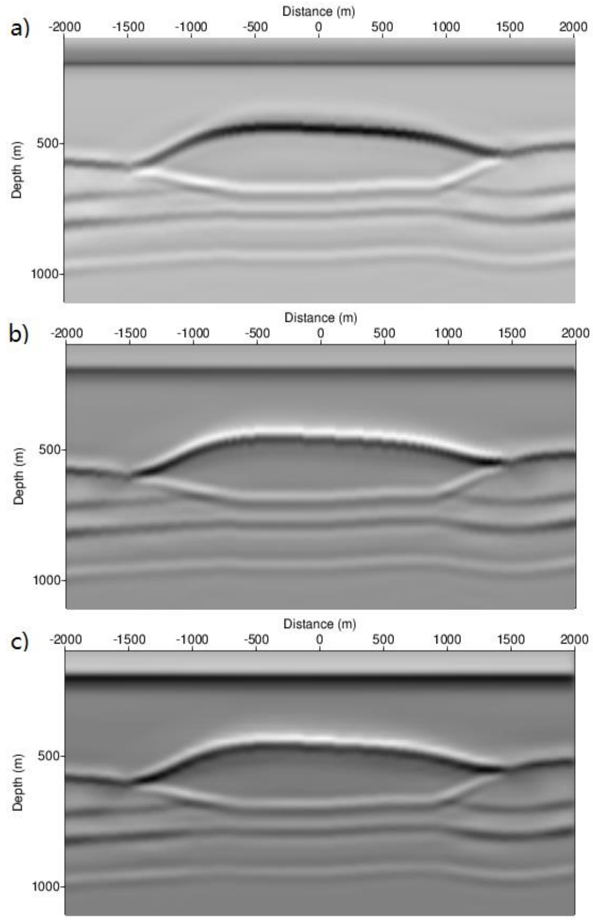

Fig 5. Target area imaging result
a) imaging result with one virtual source using true velocity; b) imaging result with one virtual source using smooth velocity; c) imaging result with four virtual sources using smooth velocity.

Conclusions

In this paper, we have applied an idea of multi-virtual sources to Marchenko imaging. As the result shown, the computational efficiency is greatly improved without influence on the image quality. The computational efficiency is related to the number of virtual sources placed in the target depth each time. However, there is a limit within which number of virtual sources be placed in the model. It would be difficult to separate the direct arrivals for too many virtual sources since they will be coupled together.

Acknowledgments

We thank Jan Thorbecke (Delft University) and Wapenaar, K (Delft University) for their help. And the work is under support of China national key project 2016ZX05031003 and key research project 2017YFB0202900.

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