Introduction

It is usually a challenging task for expanding conventional reverse time migration (RTM) methods to ambient noise seismic data. Hence, this kind of data is always regarded as noise to be removed. However, ambient noise carries a wealth of geological information of subsurface structures in many cases, especially if active-source exploration cannot be implemented. Ambient noise is a common type of passive source existing in the natural environment and seismic industry, which is of great value to be utilized. Constructing virtual shot gathers through the seismic interferometry (SI) method, for example, cross-correlation (Rickett and Claerbout, 1996), is always the first step of passive data processing, followed by the application of conventional active-source data processing methods. Artman proposed the boundary conditions used in frequency-domain one-way wave migration (Artman, 2006). This method directly uses passive source seismic data for migration imaging. The boundary conditions in this method are also applicable to ambient noise in RTM. Compared to frequency-domain one-way wave migration, RTM has a variety of imaging conditions that will affect the final imaging results. Most methods were proposed to overcome artifacts, improving image quality, and achieving the perfect balance between storage space and computational cost.

In this abstract, an RTM imaging method for ambient noise seismic data is proposed to address the shortcomings in data characteristics, including the unknown locations of ambient noise sources, low signal-to-noise ratio, unpredictable excitation time and source frequency. We introduced the multiple imaging boundary conditions of passive data. The \(f-k\) domain wavefield decomposition method was applied to effectively eliminate the low-frequency artifacts in imaging results. Moreover, the multiple segment superposition technique was applied to improve the computational efficiency and reduce the consumption of storage space. Most importantly, the full wavefield decomposition and normalized imaging conditions methods were combined to overcome the imbalance of imaging energy caused by the uneven distribution of passive sources, as well as improving the imaging quality of deep and edge area. Finally, a numerical example of the Marmousi model is given to demonstrate the effectiveness of the proposed method.

Ambient noise imaging

In Figure 1, \(x_1\) and \(x_2\) are the receivers on the free surface. Passive sources are randomly distributed in the subsurface. The excitation of sources generates upward direct wavefield \(U_0\) (Figure 1a), resulting in primary direct waves in passive transmission records. The primary is regarded as areal sources. Then it is reflected by free surface, generating downward reflected wavefield \(D_1\) (see Figure 1b). In Figure 1c, wavefield \(U_1\) is generated by wavefield \(D_1\). The records obtained by \(U_1\) is 1st order multiples. The responses of \(U_0\) and \(U_1\) are a pair of 1st order source and receiver records. Similarly, the responses of \(U_1\) and \(U_2\) are a pair of 2nd order source and receiver records.

\[ T(x,t) = U_0(x,t) + U_1(x,t) + \cdots + U_n(x,t) \]  

\(1\)

Therefore, there are \(n\)’s order source-receiver records in raw passive transmission records. The passive seismic records are expressed as (Zheng, 2015):

In this regard, source wavefield \(S(x,z,t)\) and receiver wavefield \(R(x,z,t)\) can be generated by forward and backward propagate \(T(x,t)\). Here, \(T\) is regard as source and receiver records (Zheng,
Based on cross-correlation imaging conditions (Claerbout, 1971), the ambient noise RTM formula is expressed as:

$$I(x, z) = \int S(x, z, t) R(x, z, t) dt$$

(2)

where $I(x, z)$ is the result of RTM imaging. It is worthy to emphasis that the correct results are generated by the cross-correlation of $U_n(x, t)$ forward propagation and $U_{n+1}(x, t)$ backward propagation. The incorrect order records’ cross-correlation causes artifacts. However, the artifacts can be suppressed by superposition. The reason is that the correct order’s cross-correlation produces the right information, and the others produce random noise. The superposition formula is given by:

$$I(x, z) = \sum_{i=1}^{n} \int_{nt(i-1)}^{nt(i)} S(x, z, t) R(x, z, t) dt$$

(3)

where $n$ is the number of superpositions, $nt$ is an equal difference sequence whose interval is single superposition time, and the maximum value of the sequence is the total recording time.

**Normalized full wavefield decomposition RTM**

To remove artifacts in RTM, cross-correlation is separated into four parts, which is shown as:

$$I(x, z) = \int S_d(x, z, t) R_u(x, z, t) dt + \int S_u(x, z, t) R_d(x, z, t) dt$$

$$+ \int S_u(x, z, t) R_u(x, z, t) dt + \int S_d(x, z, t) R_d(x, z, t) dt$$

(4)

where $S_d(x, z, t)$ and $S_u(x, z, t)$ are upward and downward source wavefield, respectively, $R_d(x, z, t)$ and $R_u(x, z, t)$ are upward and downward receiver wavefield, respectively. We separated wavefield in $f-k$ domain considering its high efficiency and low calculation cost.

Low-frequency artifacts are generated by cross-correlation of same direction wavefields (Liu, 2011). $\int S_u(x, z, t) R_d(x, z, t) dt$ incurs artifacts in areas with drastic velocity changes (Fei, 2015). According to the above previous researches, the formula of RTM upward and downward wavefield decomposition imaging (UD-RTM) is given by:

$$I_{ud}(x, z) = \int S_d(x, z, t) R_u(x, z, t) dt$$

(5)

Passive sources with uneven distribution may cause that energy is concentrated in a specific area. This problem can be solve using normalized imaging conditions. Compared with source wavefield normalization, receiver wavefield normalization can get high-accuracy imaging in the deep area (Kaelin and Guitton, 2006). So we combined source and receiver normalized imaging conditions, namely the normalized UD-RTM (UDN-RTM). Its imaging formula is given by:

$$I_{udn}(x, z) = \sum_{i=1}^{n} \int_{nt(i-1)}^{nt(i)} \frac{S_d(x, z, t) R_u(x, z, t)}{S_d^2(x, z, t)} dt + \sum_{i=1}^{n} \int_{nt(i-1)}^{nt(i)} \frac{S_u(x, z, t) R_u(x, z, t)}{R_u^2(x, z, t)} dt$$

(6)

With high-steep structure, upward and downward wavefield decomposition could not achieve satisfying imaging. In this regard, the wavefields are decomposed into leftward and rightward (Wang, 2016). The $S_d^2(x, z, t)$ and $S_u^2(x, z, t)$ are replaced with left and right wavefields, respectively. The imaging formulas are given by:

$$I_{ll}(x, z) = \sum_{i=1}^{n} \int_{nt(i-1)}^{nt(i)} \frac{S_d(x, z, t) R_u(x, z, t)}{S_d^2(x, z, t)} dt + \sum_{i=1}^{n} \int_{nt(i-1)}^{nt(i)} \frac{S_d(x, z, t) R_u(x, z, t)}{R_u^2(x, z, t)} dt$$

(7)

$$I_{lr}(x, z) = \sum_{i=1}^{n} \int_{nt(i-1)}^{nt(i)} \frac{S_d(x, z, t) R_r(x, z, t)}{S_d^2(x, z, t)} dt + \sum_{i=1}^{n} \int_{nt(i-1)}^{nt(i)} \frac{S_d(x, z, t) R_r(x, z, t)}{R_r^2(x, z, t)} dt$$

(8)

$$I_{rl}(x, z) = \sum_{i=1}^{n} \int_{nt(i-1)}^{nt(i)} \frac{S_u(x, z, t) R_r(x, z, t)}{S_u^2(x, z, t)} dt + \sum_{i=1}^{n} \int_{nt(i-1)}^{nt(i)} \frac{S_u(x, z, t) R_r(x, z, t)}{R_r^2(x, z, t)} dt$$

(9)

$$I_{rr}(x, z) = \sum_{i=1}^{n} \int_{nt(i-1)}^{nt(i)} \frac{S_u(x, z, t) R_u(x, z, t)}{S_u^2(x, z, t)} dt + \sum_{i=1}^{n} \int_{nt(i-1)}^{nt(i)} \frac{S_u(x, z, t) R_u(x, z, t)}{R_u^2(x, z, t)} dt$$

(10)
\[ I_{fn}(x, z) = I_{ll}(x, z) + I_{lr}(x, z) + I_{rl}(x, z) + I_{rr}(x, z) \]  

where \( S_{dl}(x, z, t) \) and \( S_{dr}(x, z, t) \) are leftward and rightward wavefields in the source downward wavefield, respectively, \( R_{dl}(x, z, t) \) and \( R_{dr}(x, z, t) \) are leftward and rightward wavefields in the receiver upward wavefield, respectively. \( I_{ll}(x, z), I_{lr}(x, z), I_{rl}(x, z), \) and \( I_{rr}(x, z) \) are imaging results of normalized cross-correlation between left-down and left-up, left-down and right-up, right-down and left-up, and right-down and right-up wavefields cross-correlation in full wavefield decomposition normal RTM (FN-RTM), respectively. The normalized full wavefield decomposition RTM (FN-RTM) imaging \( I_{fn}(x, z) \) is generated by adding four imaging results together.

**Examples**

We applied the developed method in the Marmousi model (Figure 2). The model size is \( 1210 \times 3650 \) m. Its grid spacing is 10 m. 92 receivers on the surface have the same offset, i.e., 40 m.

150 sources are randomly distributed between depths of 1000 m and 1200 m. The 100 sources of them are located in the low left area, shown in the black box of Figure 2. The other 50 sources are located in the low central area, shown in the red box of Figure 2. They have random duration times and the maximum is 60 s. The sources are Ricker wavelet convolve with random earthquake sequence. Their center frequency is randomly chosen from 12 to 24 Hz. The total acquisition time is 600 s.

**Figure 2** Grand truth model and source distribution (marked in the black and red boxes).

Figure 3a is conventional RTM with a huge amount of artifacts. Figure 3b is RTM with up and down wavefield decomposition. Both of their energy is concentrated in the lower left due to the uneven distribution of the sources. Compared with the unnormalized results (see Figure 3a and 3b), UDN-RTM and FN-RTM are normalized results in Figures 3c and 3d, respectively. Significantly, the right, marginal and deep regions are improved. The imaging amplitude via the three methods at 0.1 km of distance and true reflection coefficient is compared. The FN-RTM shows the best performance, especially in the deep area. The test results in a smooth velocity model are shown in Figure 4. Figure 4b and 4c are unnormalized RTM and normalized wavefield decomposition RTM imaging results, respectively. The results demonstrate that the normalized method has better performance.
Figure 3 Migration results with different imaging conditions with uneven distribution.

Figure 4 Smooth velocity model (a) and test results (b and c).

Conclusions

We developed the ambient noise RTM based on normalized full wavefield decomposition. Actually, it is vital to perform long-term acquisition because ambient noise with a low signal-to-noise ratio has the necessary information. In this regard, we utilized wavefield decomposition in the $f$-$k$ domain to reduce low-frequency artifacts and improve the efficiency of the developed method. The ambient noise seismic FN-RTM imaging condition formulas are derived to balance the imaging energy and improve the imaging accuracy in deep areas. The multiple segment superposition overcame artifacts and saved storage spaces.

References


