3D seismic residual statics solutions by applying refraction interferometry

Han Gao, and Jie Zhang, University of Science and Technology of China (USTC)*

Summary

We apply interferometric theory to solve a 3D seismic residual statics problem that helps to improve reflection imaging. The approach can calculate the statics solutions without picking the first arrivals in shot or receiver gathers. The statics accuracy can be improved significantly since we utilize stacked virtual refraction gathers for calculation. Because sources and receivers can be placed at any position in a 3D seismic survey, the arrival times of virtual refractions for a pair of receivers or sources are no longer the same as in a 2D case. To overcome this problem, we apply 3D Super-Virtual Interferometry (SVI) method in the residual statics calculation. The virtual refraction for the stationary source-receiver pair is obtained by an integral along source or receiver line without the requirement of knowing the stationary locations. Picking the max-energy times on the SVI stacks followed by applying a set of equations is able to derive reliable residual statics solutions. We demonstrate the approach by applying to synthetic data as well as real data.

Introduction

Rugged topography and complex near surface layers are some of the important challenges that we are facing in seismic data processing today. Residual statics due to near-surface velocity variations may not be able to be resolved through the near-surface model imaging, but critical for seismic data processing.

There are many methods to calculate residual statics solutions, such as reflection stack-power maximization method (Ronen and Claerbout, 1985), refraction waveform residual statics (Hatherly et al., 1994), and refraction traveltime residual statics (Zhu and Luo, 2004). For refraction methods, the accuracy of the refraction static correction largely depends on the quality of the first arrival traveltimes. However, seismic amplitudes at far offsets are often too weak to pick. To overcome this problem, the theory of Super-Virtual Interferometry (SVI) is developed to generate head-wave arrivals with improved SNR (Bharadwaj and Schuster, 2010). The SVI method is later used to calculate 2D residual statics solutions without picking first arrivals (Zhang et al., 2014). In this study, we follow Lu et al. (2014) to extend SVI to 3D and apply that to solve a 3D residual statics problem.

In 2D cases, all the refractions from the same layer partly share common raypath, and are called stationary. As a result, for a pair of source and receiver the arrival times of virtual refractions are always the same. They can be stacked to enhance the SNR. However, in 3D cases, the source-receiver pairs are not at stationary positions any more. To overcome the problem, a 3D SVI method is developed (Lu et al., 2014). The stationary virtual refraction trace is obtained by integrating over the source lines or receiver lines, without the requirement of knowing the locations of stationary sources or receivers. We combine the 3D SVI method with interferometry residual statics method (Zhang et al., 2014) to derive 3D surface-consistent residual statics.

Theory

Figure 1 describes a procedure for creating 2D virtual refractions for source and receiver pairs (Bharadwaj and Schuster, 2010), all the related refractions partly share common raypath. We need SVI for the purpose of calculating residual statics rather than enhancing the long-offset refractions. Obtaining SVI is our first step. However, in most 3D cases, source lines are perpendicular to receiver lines. It is impractical to find particular stationary sources and receivers. Thus, calculating 3D SVI is difficult. Fortunately, Lu et al. (2014) develop an approach to solve the problem by applying stationary phase integration (Schuster, 2009) to the source and receiver lines. We follow their approach for the first step.

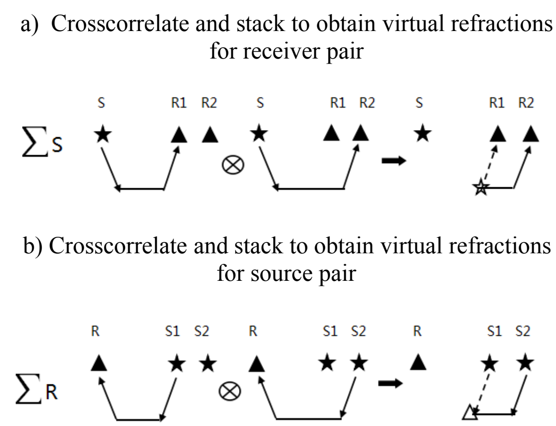
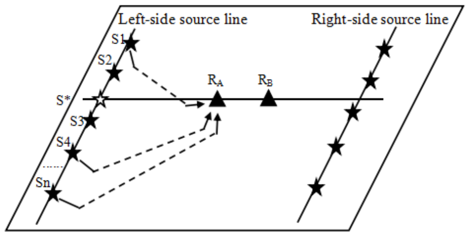


Figure 1: a) Correlation of the recorded trace at R_1 with that at R_2 for a source at S to give the virtual refraction trace. Stack the results for all post-critical sources will enhance the SNR of the virtual refraction by $\sqrt{N}$. b) Similar to that in a. Here, N denotes the number of coincident source or receiver positions that are at post-critical offset.

Figure 2 illustrates the procedure to do 3D SVI. For two adjacent receivers (R_A and R_B) along the same receiver line and the chosen source line (for example, the left-side source line displayed in Figure 2), we calculate the cross-correlation result of trace SR_A and SR_B for each source along the line. The stack of the cross-correlation results for the whole line approximate the virtual refraction generated by the cross-correlation of S^*R_A and S^*R_B multiplied by a coefficient. Where S^* is a stationary source associated with the given receiver R_A and R_B. The phase of the stacked trace is accurate comparing with the stationary virtual trace, while the amplitude is much improved. Since the stationary points are along the receiver line and do not depend on which source line we choose, we can stack the result of several lines to further improve the result.

a) Geometry of CRG R_A



b) Geometry of CRG R_B

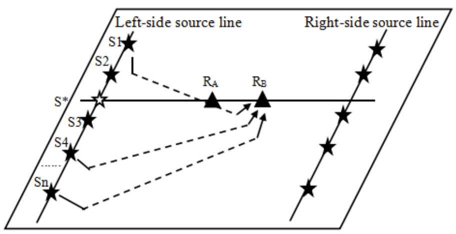


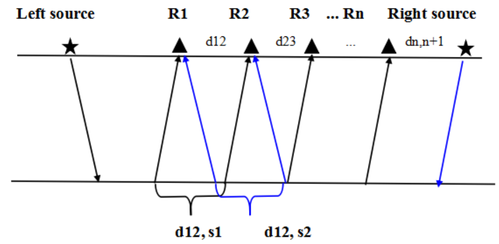
Figure 2: Geometry of sources and receivers. One left-side source line and one right-side source line for the receiver pair are shown. a) Geometry of a common receiver gather for receiver R_A and the integrated source line. b) Geometry of a common receiver gather for R_B and the integrated source line. The hollow star represents one of the stationary sources for the chosen receiver pair.

We can integrate along either left-side source lines or right-side source lines to obtain the stationary virtual trace of left and right sources respectively. The traveltime of maximum energy of each trace is the required stationary forward (left) and backward (right) traveltime difference.

The procedure of generating virtual refraction of stationary source pair is the same. For each adjacent source pair, we calculate the cross-correlation for every receiver along the receiver line and stack the results. The results of several receiver lines of either left-side or right-side are supposed to be stacked respectively to obtain more accurate traces.

Figure 3 shows a schematic illustration of refraction raypath in a simple layer model. At this point, the 3D problem is turned into a 2D problem. We can apply the equations in Zhang et al. (2014) to derive slowness values underneath the refractor. The traveltime difference between two adjacent receivers/sources (R1 and R2) decomposes on: 1) the horizontal segment; 2) the difference of two upgoing/downgoing raypaths to R1 and R2 respectively. Then, we set up Equation 1 that includes residual statics:

a) Raypath of stationary source-receiver pair



b) Raypath of stationary receiver-source pair

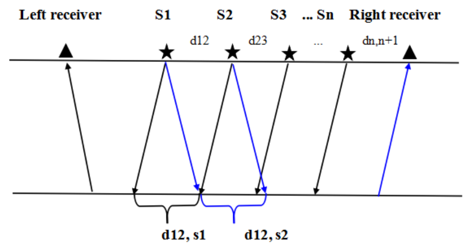


Figure 3: a) Sketch for receiver pair obtaining the signal from both left and right sources, black line represents the refraction raypath from the left source and blue line denotes the signal from the right source. b) Sketch for source pair generating the signal to both left and right receiver, black line represents the refraction raypath to the left receiver and blue line denotes the signal to the right receiver.

$$\begin{aligned} &stat(2) - stat(1) = \Delta T_{12} - d_{12} s_1 \\ &stat(3) - stat(2) = \Delta T_{23} - d_{23} s_2 \\ &\ldots\ldots \\ &stat(n+1) - stat(n) = \Delta T_{n,n+1} - d_{n,n+1} s_n \end{aligned} \qquad (1)$$

where stat(n) is the residual statics at the location of receiver/source n, respectively; $\Delta T_{n,\ n+1}$ represents stationary traveltime differences between receiver/source n and n+1 from left stationary sources, which can be obtained by 3D SVI. $d_{n,n+1}$ denotes the distance interval between two adjacent receivers/sources, and S_n is the slowness along refraction path. Shown in Figure 3, each receiver/source pair receive/generate signal from/to both left and right sources/receivers. Assuming upgoing/downgoing raypaths from left and right to the same receiver/source equal, we have Equation 2:

$$\begin{aligned} &stat(1) - stat(2) = \Delta T_{21} - d_{12} s_2 \\ &stat(2) - stat(3) = \Delta T_{32} - d_{23} s_3 \\ &\ldots\ldots \\ &stat(n) - stat(n+1) = \Delta T_{n+1,n} - d_{n,n+1} s_{n+1} \end{aligned} \qquad (2)$$

Where $\Delta T_{2,1}$ denote the traveltime differences between R1 and R2 from right stationary sources/receivers. Combining Equation 1 and Equation 2, we then obtain Equation 3:

$$
\begin{aligned}
s_1 + s_2 &= (\Delta T_{12} + \Delta T_{21}) / d_{12} \\
s_2 + s_3 &= (\Delta T_{23} + \Delta T_{23}) / d_{23} \\
&\ldots\ldots \\
s_n + s_{n+1} &= (\Delta T_{n,n+1} + \Delta T_{n+1,n}) / d_{n,n+1}
\end{aligned}
\quad (3)
$$

To obtain the stationary traveltime difference $\Delta T_{n,n+1}$ and $\Delta T_{n+1,n}$ from left-side sources/receivers and right-side sources-receivers for each receiver/source pair, we can integrate along left-side source/receiver lines and right-side source/receiver lines respectively. Then we can pick the traveltime of maximum energy of each trace, which is the required traveltime difference.

If we assume that s_1 is equal to s_2, then we can calculate all slowness values by the recursive formula. Assuming the residual statics value of the first receiver/source zero, we can derive statics for the remaining receivers /sources iteratively.

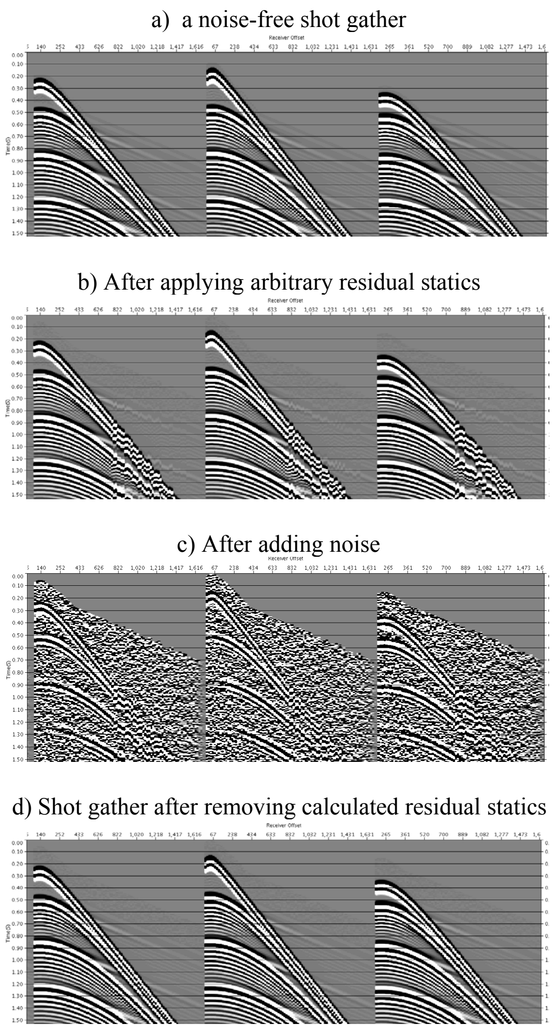


Figure 4: a) A noise-free shot gather b) Apply arbitrary statics between -20 ms and 20 ms to the shot gather c) Add random noise with signal-to-noise ratio of 2 to the shot gather d) The shot gather after removing calculated residual statics

Synthetic Data Test

To demonstrate the effectiveness of our method, we apply it to a synthetic example first. We generate common shot gathers by a finite-difference solution to the 3-D acoustic wave equation using a simple velocity model with two layers. We build a perpendicular geometry system similar to real cases. For each source, we have a template of 10 receiver lines and 160 receivers along each line. We select 123 receivers of far offset along 3 receiver lines (41 along each line) to derive receiver residual statics. A total of 6 source lines (3 source lines on each side) are selected to be integrated.

Figure 4(a) shows a noise-free shot gather, and in Figure 4(b) the same gather is applied with surface-consistent residual statics at far offset with arbitrary statics between -20 ms and 20 ms. Then random noise with signal-to-noise ratio of 2 is further added to data as shown in Figure 4(c). We can see that the first arrivals are difficult to be picked due to poor signal quality. We roughly mute the data and keep the early arrivals. Applying our method, we obtain the result after removing the calculated residual statics, as shown in Figure 4(d). We can see that the traveltimes of the shot gather are smoother, which proves the effectiveness of the new method.

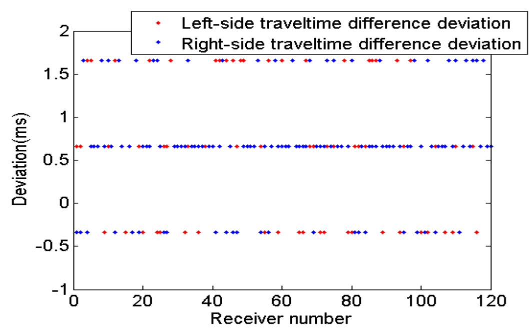


Figure 5: Traveltime difference deviation from stationary traveltime difference for each receiver pair after applying 3D SVI.

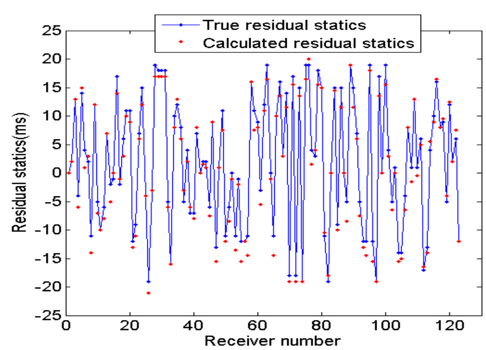


Figure 6: Comparison between true residual statics and calculated residual statics.

Figure 5 shows the traveltime difference deviation from stationary sources for each receiver pair after adding an arbitrary statics and noise of both left-side sources and right-side sources due to applying 3D SVI. Figure 6 shows the true residual statics applied to data, and the calculated residual statics. In Figure 7, their differences are plotted as well, and it shows that the differences are less than 3.5 ms.

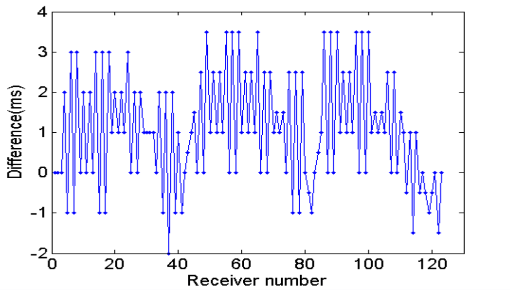


Figure 7: Difference of true residual statics and calculated residual statics.

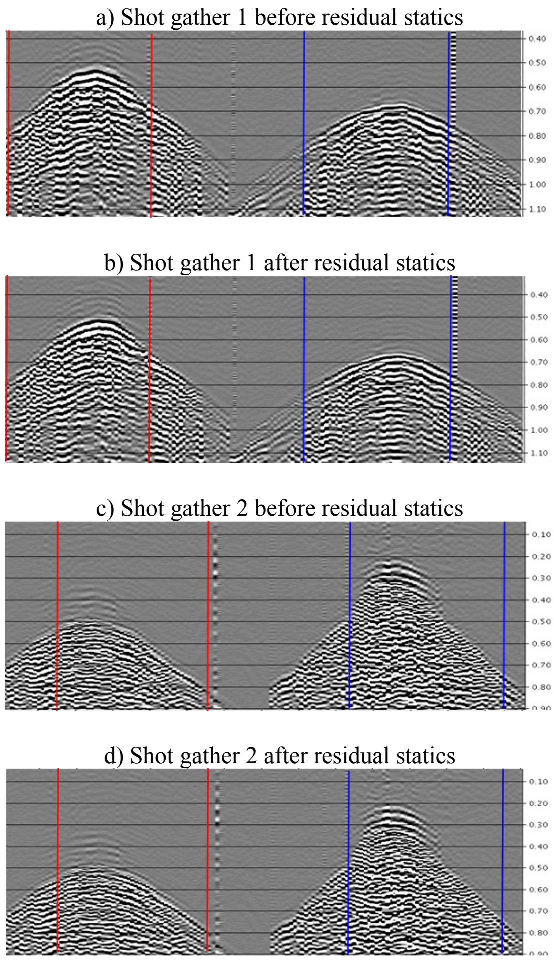


Figure 8: a) Shot gather 1 before residual statics. b) Shot gather 1 after applying residual statics. c) Shot gather 2 before residual statics. d) Shot gather 2 after applying residual statics. The traces between two red/blue lines are received by receivers after applying residual statics.

Field Data Test

We demonstrate the statics solutions using a real dataset acquired in Africa. We choose 80 receivers along 2 receiver lines to apply residual statics. Figure 8(a), Figure 8(c) present two shot gathers before residual statics, while Figure 8(b), Figure 8(d) show the result after applying residual statics. The comparison indicates the continuity of the first arrivals is improved with the statics applied.

Conclusions

We develop a 3D residual statics approach that applies 3D SVI to help the calculation of residual statics. The approach can handle very noisy data in which the first arrivals are hard to pick. Tests with synthetics and real data suggest that the method is effective. The drawback of this method is that the result may be affected by a coarse spacing of sources or receivers, especially when the exploration template area for source is small.

Acknowledgments

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