Enhancement of a thumper source far offset refracted phases using super virtual interferometry (SVI)

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Super-virtual interferometry (SVI) is a technique in which cross-correlation between consecutive receiver responses is carried out to obtain the virtual head-wave arrivals, which are then convolved with the initially recorded traces to get the super-virtual trace. SVI can be used to enhance the refracted phases by stacking all the arrivals acquired using multiple shots at one position, leading to an improved SNR by a factor of $\sqrt{n}$, where ‘n’ is the number of sources and receivers to generate the head-waves. In this study, we have generated few synthetic common shot gathers (CSGs) using forward modelling over a three-layer velocity–depth model with an embedded spherical anomaly, a complex five-layer velocity–depth model and the Marmousi model. Certain amount of noise is added on these gathers and then SVI technique is applied on the gathers which has resulted in an improved SNR of refracted phases at the far offset. We have further tested this technique on a field dataset acquired from the Kumaon Himalayan region using a 450 kg thumper as an energy source and 111 active channel remote acquisition unites (RAUs) with 5 Hz geophones as sensors. The resulting SVI gathers show the refracted arrivals more clearly. Continuity in the phases is increased after stacking and iterative SVI.

Keywords. Thumper; refraction; RAU; Marmousi model; Himalayan; iterative SVI.

1. Introduction

Seismic surveying is vital in producing sub-surface images which are helpful in carrying out exploration activities for oil and gas (O’Brien 1983) and mineral deposits (Malehmir et al. 2012). To study subsurface velocity and layer interface structure one should analyze the refracted phases or head wave arrivals at the surface of the earth as these phases are sensitive to the changes in velocity distribution (Berg and Long 1966). Head-wave arrivals are waves which follow the path of a diving wave down to the interface and up to the surface refracting along the interface (Mallinson et al. 2011). This technique is crucial in carrying out near surface to deep crustal studies including locating buried archaeological sites (Arciniega et al. 2009), assessing subsurface geological hazards (Benson and Mustoe 1991), defining aquifer geometry (Haeny 1986), exploring for natural resources (O’Brien 1983; Malehmir et al. 2012), studying subduction plate geometry (Curray et al. 1977), and so on. Generally, in a layered medium where the velocity increases with increasing depth, after cross-over distance, refractions are the first arrivals to be recorded at the receivers and are picked for the travel time tomography inversion (Zhang and Toksöz 1998). While carrying out controlled source refraction studies (Cho et al. 2006), suppression of signal strength of far offset traces is observed and thus is a common problem to deal with. To mitigate this, either one should use a
more powerful source (Sopher et al. 2014) or try to improve the SNR of such phases (Bharadwaj et al. 2011). More powerful source brings more expenses and greater risks, hence it cannot be a wise option all the time. It is thus better to work on the data acquired as it is and improve the signal strength with all the available knowledge of seismic data processing.

Recently, seismic interferometry, which involves the cross-correlation of responses at different receivers to obtain the Green’s functions between these receivers (Wapenaar et al. 2010), has been proven to be a reliable technique to enhance the signal-to-noise ratio (SNR) of the recorded phases (Dong et al. 2006; Nichols et al. 2010; Bharadwaj et al. 2011; Mallinson et al. 2011; Hanafy and Al-Hagan 2012; Place and Malehmir 2016). The technique can be applied to both controlled-source seismic (Schuster 2001; Bakulin and Calvert 2004) and passive (ambient seismic noise or micro earthquake responses) seismic dataset (Campillo and Paul 2003; Shapiro and Campillo 2004; Sabra et al. 2005). In this technique, firstly summation of cross-correlation of two receiver responses is carried out to obtain virtual traces, followed by the convolution of virtual traces with original responses (figure 1) to obtain an improved refracted arrival at the far offset (Bharadwaj et al. 2011). Dong et al. (2006) further used this technique to distinguish between head-wave and diving wave arrivals which helped in determining the nature of the refracting boundary. Moreover, Nichols et al. (2010) used this technique for delineating the variable depth to the water table at Boise Hydro Geophysical Research Site, while Place and Malehmir (2016) used it for retrieving the first arrivals at far offset in a hard rock environment using the controlled source data acquired over the iron-oxide apatite-rich deposit at Grangesberg (Sweden) and its mining-induced structures.

In this paper, we have presented the theory of super-virtual interferometry through three synthetic datasets comprising of three simple to very complex velocity models and a real dataset acquired from the Kumaon Himalayan region in Nainital district of Uttarakhand. The innovative part of this work is that the 2D seismic data were acquired using an electronic seismic source (ESS1000 turbo) with a 450 kg hammer mounted on it. The data were sensed using wireless Remote Acquisition Units (RAU) with 111 single component geophones of 5 Hz natural frequency. We have written a prototype for the algorithm of super-virtual interferometry in Fortran 90 using OpenMP (Open Multi-Processing) which makes the program run faster than a serial program for larger datasets. OpenMP enables each thread of a system to share the workload of a program uniformly and provide the result of a computation in the smallest runtime possible. A ‘number of shots vs. time taken’ plot is shown in figure 2, which compares the time taken by a serial program and an OpenMP program for different sizes of dataset. General equations of discrete cross-correlation and convolution in time domain are used for the program. We aim to obtain an improved gather of synthetic and real datasets after applying SVI. A key observation in this paper is to get the best possible visualization of the super-virtual gathers by stacking the individual gathers of different shots at the same shot location and by applying iterative SVI (Al-Hagan et al. 2014).

Figure 1. Schematic diagram showing steps of SVI technique. Red star: source, black triangles: receivers. First, signal responses at R2 and R1 due to shooting at S are cross-correlated to get the virtual trace from S'. Second, virtual trace is convolved with the actual trace at R1 to get the original signal from R2 with enhanced SNR by a factor of $\sqrt{n}$, where $n$ is the number of sources and receivers to generate head-waves (modified after Place and Malehmir 2016).
2. Theoretical background

2.1 Forward modelling

In order to extract subsurface information of an area, forward modelling is done to predict how the seismic wavefields are affected by complex subsurface structures. The elastic form of wave equation follows a simple partial differential equation (equation 1),

$$\rho \frac{\partial v_i}{\partial t} = \frac{\partial \sigma_{ij}}{\partial x_j} + f_i,$$

where $\rho$ is density, $v_i$ is displacement velocity, $\sigma_{ij}$ is stress tensor and $f_i$ is the body forces in which the stresses are explained by the linear stress-strain relationship (equation 2),

$$\sigma_{ij} = \lambda \delta_{ij} + 2\mu \epsilon_{ij},$$
where \( \lambda \) and \( \mu \) are the Lamé parameters, \( \epsilon_{ij} \) is the strain tensor and \( \theta \) is the dilatation. For numerically solving the equations of motion, equations (1 and 2) must be discretized in time and space.

Various seismic wave modelling techniques have come up but the explicit finite difference (FD) method for seismic wave modelling in 2-D elastic medium has been accepted widely because of its accuracy in models of heterogeneous realistic (complex) media (Bohlen et al. 2015). Here, we have used the FD method that uses a system of first order coupled elastic equations where stresses and velocities are the variables (equation 1). In this scheme, they have used the staggered-grid finite difference scheme (Madariaga 1976; Virieux 1986; Levander 2001; Robertsson et al. 1994) which explained the normal stresses and shear stresses in different nodes. However, a main drawback of FD method persists that it requires a large amount of computational resources for modelling of realistic or complex models (Bohlen et al. 2015). Such computational requirements are often not fulfilled by a single personal computer or a workstation, hence either a cluster of workstations is required or some technique is needed to efficiently do the modelling. Message passing interface (MPI) (Bohlen 2002) can benefit the faster FD modelling by sharing the workload on each workstation of a cluster connected by an in-house network which can reduce the run time and increase the grid sizes significantly. The shot gathers generated after the forward modelling is used for super-virtual interferometry which is discussed in the following section.

2.2 Theory of super-virtual interferometry

SVI is a two-step process: first, the seismic signals recorded at different receiver positions are cross-correlated and summed in order to generate virtual source seismograms and the second step is to convolve these virtual traces with original data to get the super-virtual traces for head-wave arrivals (Bharadwaj et al. 2011). It enhances the signal to noise ratio (SNR) by a factor of \( \sqrt{n} \), where \( n \) is the number of sources and receiver pairs. This technique is based on the Rayleigh’s acoustic reciprocity theorem and time-reversal invariance principle which states that the Green’s function between two receiver pairs is the integration of cross-correlation of traces observed at those receivers (Wapenaar and Fokkema 2006). Bharadwaj et al. (2011) found an innovative way of using this reciprocity theorem for generating the super-virtual refractions at far offsets by convolving the generated virtual traces with the original traces as shown in figure 1. A flowchart discussing the necessary steps and equations for SVI is described in figure 2. Equations mentioned in the flowchart are a schematic representation of how the virtual and super-virtual arrivals are generated using cross-correlation and convolution in time domain.

To provide an idea about the general mathematics behind its theory (in frequency domain), we restate the equations (based on our model shown in figure 1) as described by Dong et al. (2006) and Mallinson et al. (2011).

Generally, in a complex layered sub-surface medium, refraction arrivals are the first ones to get recorded at geophones in a seismic survey (Mallinson et al. 2011). Waves travelling down a layer with low velocity and along the refractor with a higher velocity get refracted upward as head waves. Consider a head wave with its arrivals at \( R_2 \) and \( R_1 \) from a common source \( S \) as:

\[
u(S, R_2) = A(S, R_2)e^{i\omega(t_{SS}+t_{SSR_2})},\]

and

\[
u(S, R_1) = A(S, R_1)e^{i\omega(t_{SS}+t_{SSR_1})},\]

Cross-correlation of these two signals generates a virtual head wave refraction as shown in figure 1:

\[
\varphi(R_1, R_2)_S = \nu(S, R_2)^*\nu(S, R_1),
\]

where \( t_{SS} \) is the travel time from \( S \) to \( S' \), \( t_{SR} \) is the travel time from \( S' \) to \( R_2 \), \( t_{SR_1} \) is the travel time from \( S' \) to \( R_1 \), and \( A(S, R_2) \) and \( A(S, R_1) \) are amplitude terms which are taken to be equal for simplification.

In order to determine the super-virtual refraction, the original signal \((\nu(S, R_1))\) is convolved (*) with the generated virtual refraction \((\varphi(R_1, R_2)_S)\):

\[
\psi(S, R_2)_{R_1} = \nu(S, R_1)\varphi(R_1, R_2).
\]

\[
\psi(S, R_2)_{R_1} = A(S, R_1)\frac{e^{i\omega(t_{SS}+t_{SSR_1})}}{A(S, R_1)}\times |A(S, R_1)|^2e^{i\omega(t_{SSR_2}+t_{SSR_1})},
\]

\[
\psi(S, R_2)_{R_1} = A(S, R_1)|A(S, R_1)|^2e^{i\omega(t_{SS}+t_{SSR_1})}.
\]

Summing up both virtual and super-virtual refractions for \( n \) number of source-receiver pairs.
will give a kinematically identical signal as that of the original data \(u(S, R1)\) with an enhanced SNR.

3. Results and discussion

Firstly, we have carried out the synthetic tests followed by the real data analysis. In the synthetic tests, described in sections 3.1–3.3, the shot gathers are generated using forward modelling described in section 2.1 in which a certain percentage of noise is added and then the SVI is performed following the flowchart described in section 2.2. The modelling parameters for synthetic tests are explained in sections 3.1–3.3. For real data analysis, we directly used the acquired gathers for SVI and is explained in section 3.4.

3.1 Synthetic test 1

For a simple case, a three-layer velocity–depth model having constant velocity and density in each layer and a spherical anomaly in the second layer is generated (figure 3). Spherical anomaly lies at a depth of 350 m. Parameters are set to mimic the marine acquisition survey with hydrophone streamer and sources both lying in the water layer at a depth of 10 m. The top layer in the model consists of a 200 m thick water layer followed by a 300 m thick layer containing the spherical anomaly and a 400 m thick bottommost layer. Model is generated using the grid parameters discussed in table 1.

A typical common shot gather obtained from forward modelling is shown in figure 4. There are 320 receiver channels (thus 320 traces), marked by the thick blue line, spaced at every 12.5 m and 70 shots, marked by the red star, fired at a spacing of 50 m (figure 3). The shooting geometry is kept as end on spread.

Ten percent of Gaussian noise is then added to all the synthetic gathers (figure 5a) to suppress the signal strength of refracted phases. Then the SVI is applied to the noisy gathers in order to improve the refracted phases at the far offset. A super-virtual gather is shown in figure 5(b) and one can clearly see that the signal strength is improved significantly starting from the 200th trace up to the last.

Figure 3. Three-layer velocity–depth model used for generating common shot gather (CSG) in figure 4. Velocity of each layer and the embedded sphere is mentioned along with the depth. Source array of 70 shots starts from \(S1\) (marked by red star) and hydrophone streamer of 4000 m length is represented from \(R1\) to \(R320\) (marked by blue solid line). Shot spacing is 50 m and receiver spacing is kept as 12.5 m. Both source and receiver array are kept at a depth of 10 m from the free surface.

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Figure 4. Raw interpreted synthetic shot gather generated from three-layer velocity–depth model. Some of the reflections in increasing depth look like multiples.

Figure 5. (a) Synthetic CSG after addition of 10% of noise on the shot gather explained in figure 4. (b) Super-virtual CSG with an enhanced SNR. Red lines bound the refracted phase. Refraction phases are greatly improved till the last receiver. Signal strengths of the reflected phases are also enhanced.

Figure 6. Five-layer complex velocity–depth model used for developing CSG in figure 7. Velocity of each layer and anomaly is mentioned in the legend. Depth of the layers vary along the model length. A shot position (S4) is marked by a red star and the hydrophone streamer of 4000 m length is extended from R1 to R320, marked by blue solid line. Shot and receiver spacing is 50 and 12.5 m, respectively, and both shot and receivers are placed at a depth of 10 m in the water layer.
trace. One can further notice that the SVI has reduced the random noise and improved the signal strength for the reflected phases (Figure 5b).

3.2 Synthetic test 2

A more complex velocity–depth model (Figure 6) is generated for further testing the efficiency of the algorithm after a simple velocity model. Here, the velocity model consists of five layers instead of three as in the previous case. The layers are undulated and are inserted with randomly shaped anomalies to create a real scenario of the sub-surface. For instance, dykes have been inserted in the form of anomalies having the velocity (4700 m/s) and density (3164 kg/m³) greater than that of the surrounding host rock. The dimension of this model, described in Table 1, is a bit larger than that of the previous one. The first layer of this model is a water layer of thickness of 300 m. Shooting from an airgun and recording by hydrophone streamer are done in the water layer at a depth of 10 m. Velocity in each layer and anomalies are different and are mentioned in the legend of Figure 6.

Forward modelling as discussed in section 2.2 is done using the five-layer complex velocity–depth model to generate synthetic shot gathers, an example of which is shown in Figure 7. Number of receivers or traces and shots are 320 and 70, respectively. Group interval and shot interval are 12.5 and 50 m, respectively. SVI is applied on the

Figure 7. Raw interpreted synthetic shot gather generated from five-layer velocity–depth model described in Figure 6.

Figure 8. (a) Synthetic CSG (explained in Figure 7) after addition of 15% Gaussian noise. (b) Super-virtual CSG with an enhanced SNR. Blue lines bound the refracted phase. Refraction phases are significantly improved till the last receiver.
gathers after adding 15% random noise to suppress the far offset refracted phases (figure 8a). An increase in SNR after applying SVI is evident from near 200th trace up to the end. The technique has shown promising results even for a complex model and hence it can be said that SVI is helpful for any medium which can generate head wave arrivals.

3.3 Synthetic test 3

At last we have used the Marmousi velocity–depth model for the synthetic tests (figure 9). The model was generated back in 1988 by Institute Francais du Petrole (IFP). The geometry and velocity–depth model were made such as to produce complex seismic dataset on which all the processing techniques can be used to get a correct image of earth (Versteeg 1994). Hence, the geometry of the model is based on a profile through the North Quenguela trough in the Cuanza basin. Numerous large normal faults and tilted blocks in the model are due to its resemblance to the actual continental drift geological setting. The data have been generated using a 2D acoustic finite-difference modelling program (Alkhalifah et al. 1997). The model is proved to be a very useful dataset for various companies and research or academic institutions. A lot of work has been carried out on the dataset by universities and oil companies. The model is 9.2 km long and represents a depth of 3 km. The model contains 158 horizontally layered horizons. Velocity in the model strongly varies from 1500 to 5500 m/s in both vertical and lateral directions. One of the biggest motivations to use the Marmousi model or any other complex velocity model is that the first arrivals of such models are not the most energetic ones (Geoltrain and Brac 1993). Hence, this model will be the most suitable one to judge the efficiency of the SVI algorithm improving the refracted phases at the far offset.

Shot gathers for the Marmousi model are made available due to the released courtesy of Amoco and BP. The data is acquired such that it has both ends on and split spread gathers. Sample interval of data is 4 ms with 725 samples per trace. There are 207 geophones per shot and 287 shots were fired (figure 10). We have introduced 2% of noise in the shot gather (figure 11a). As expected, the refracted phases are not quite energetic in terms of signal strength. SVI is then applied on the noisy gather and it enhances the refracted phases at the far offset bounded by the red lines (figure 11). An increase in SNR after applying SVI is also observed in figure 11(b) from 350th trace up to the end. Again, one can notice the reflected arrivals are more prominent and random noise is suppressed substantially in the SVI gather.
3.4 Real data analysis

The mentioned SVI method is now applied on a field dataset collected from the foothills of Kumaon Himalayan region in Nainital district of Uttarakhand (figure 12). The data were acquired using a 450 kg seismic hammer (ESS1000 turbo) as a source and Sercel’s Remote Acquisition Unites (RAU) and geophones with 5 Hz natural frequency. The field data were recorded by 111 active receivers with a group interval of 40 m and 36 shots at 18 shot points each spaced at 40 m.
Two shots were fired at each shot point which were later stacked for enhancement of SNR and removal of random noise. Near offset while acquisition was kept at 80 m, the far offset was maintained at 4480 m. Roll over of the entire arrangement for 40 m was performed after each shot. Sampling interval of the data was set as 1 ms. SVI is applied to the gathers from first shots fired at each shot point, then to the stacked gathers of two shots fired at each shot position and finally to SVI gathers obtained from the raw data (iterative SVI). In all the gathers refracted phase is suppressed by random noise at far offset and hence accurate travel time cannot be picked for travel time tomography. 2D seismic data acquired from the field is represented as common

Figure 13. Shot gather focusing on the refracted phase: (a) raw shot gather and (b) super-virtual gather with an improved SNR.

Figure 14. (a) Stacked raw shot gather and (b) super-virtual gather with an improved SNR and continuity starting from the first trace.
shot gather which contains ground roll and random noise which suppresses the amplitude of far offset refraction phase. Ground rolls are removed as a part of pre-processing of the field data. Due to a thick weathered layer in the area, strong reflection events cannot be seen.

Data acquired from field does not show a continuity in the traces and noise dominates the signal. SVI is applied to improve the continuity and to enhance the SNR. As mentioned earlier that two shots were fired at each source location with an interval of approximately 15 s, SVI is first applied to gathers from the first shot and then to the stack of both the shots (figures 13 and 14). This has shown an improved quality of super-virtual gathers. A strong continuity is a result of stacking. Finally, SVI gathers along with raw data are fed into the program to perform iterative SVI and the phases are very much improved. Prominent refracted arrivals could only be obtained up to a few near offset traces where noise could not dominate the signal. After around 45th trace, noise started suppressing the signal (figures 13a, 14a and 15a). Application of SVI and its iteration enhanced the signal significantly up to ~60th trace in the SVI gather (figures 13b, 14b and 15b).

From these tests it is clear that the SVI technique can be used to improve the SNR of the refracted phases. The travel time of the enhanced refracted arrivals then be accurately picked using any automatic picker and proceed for travel time tomography to delineate the subsurface velocity distribution and thus will also have significant implications in delineating velocity–depth models for shallow-land or marine hydrocarbon-bearing reservoirs.

4. Conclusions

We have presented the theory of super-virtual refraction interferometry through three synthetic tests and a real data example in which the SNR of head-wave arrivals enhances at far offset which is proportional to a factor of \( \sqrt{n} \), where \( n \) is the number of source-receiver pairs generating head-waves. Iterative SVI has further increased the quality of data particularly for refracted phases to be picked for travel time tomography. This technique can be applied to any medium generating head-wave arrivals. Results from synthetic and real data examples have shown few significant benefits of SVI: (1) enhanced SNR of far offset traces for accurate picking of first arrival travel times of noisy traces, (2) stacking of multiple shot gathers produces a super-virtual gather with even more enhanced refracted phases than pre-stack ones, and (3) successive iterations of super-virtual gathers improves the SNR manifolds. Parallel programming using OpenMP
helps in faster computation of larger datasets which is not possible by serial programming.

One of the problems associated with this technique is that there will be artefacts in super-virtual gathers due to limited number of source-receiver pairs and a coarse spacing between them. Windowing around head wave arrivals can be one of the possible remedies to this problem.

In future, first arrival travel times can be reliably and accurately picked for travel time tomography from the improved gathers using super-virtual interferometry. This will provide a detailed depth–velocity structure of subsurface which will help in delineating the subsurface geology. Tomography can lead us to perform full waveform inversion in future. Furthermore, this technique can be tested on wide-angle surveys carried out using deep ocean bottom seismometers in marine or vibroseis/explosives on land.

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