Deblending in common receiver and common angle gathers

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ABSTRACT

In specific seismic acquisition scenarios, such as ocean bottom node (OBN) surveys, there are more sources than receivers. This imbalance can be an issue since the efficiency of conventional deblending, and migration algorithms in common shot gathers (CSG) is related to the number of available traces (fold) in this gather. Therefore, we need to develop new deblending and migration algorithms that process data in domains other than CSG. Preferably, domains that have higher fold numbers than the CSG for these acquisition scenarios. Due to reciprocity, common receiver gathers (CRG) is equivalent to common shot gathers. Therefore, migration in the CRG domain is very similar to conventional migration in the CSG domain. Moreover, in the OBN case, reverse time migration (RTM) in the CRG domain saves significant memory and computational time compared to the CSG domain since the number of receivers is much smaller than the sources. Furthermore, blending interferences have an incoherence structure in CRG due to random time delays between sources, significantly improving deblending performance. This report investigates the efficiency of RTM and least-square RTM in the CRG domain as a deblending tool. Additionally, we investigate the suitability of other domains such as common midpoint gather (CMG) and common angle gather (CAG), as another domain for deblending using RTM.

INTRODUCTION

In both land and marine seismic surveys, the number of receivers is much larger than the number of sources. The imbalance between the sources and receivers is because additional receivers' cost is much lower than additional sources. However, this imbalance between the receives and the sources is much worse for ocean bottom acquisition (OBN). In OBN acquisition, the number of receivers is limited due to cost(Beaudoin and Ross, 2007), as shown in Figure 1, which reduces the illumination of the subsurface significantly.

Despite its high cost, ocean bottom node surveys (OBN) have many advantages compared with conventional marine acquisition (Barkved, 2012). First, the signals on the seabed are quieter than those on the water surface. Second, OBN could cover more areas around platforms to gather data with wider azimuth and longer offsets than normal marine acquisition (Koster et al., 2000). Third, OBN could record shear wave (Thomsen et al., 1997). And OBN may attenuate multiples by separating upgoing and downing waves (Barr and Sanders, 1989). However, the coarse sampling of receivers and the reduced illumination requires changes to standard processing and migration algorithms. Several variants of OBN processing methods have been suggested to improve OBN results (Amundsen et al., 2001; Nemeth et al., 1999; Verschuur and Berkhout, 2011). For example, the first multiple of the data (receiver ghost) can be processed and migrated instead of the primaries to increase illumination. Nonetheless, there is still a large list of OBN surveys' challenges awaiting to be solved (Dellinger, 2016).

Two popular algorithms for prestack imaging by downward continuation are shot-geophone migration and shot-profile migration. Shot-geophone migration utilize the double square-

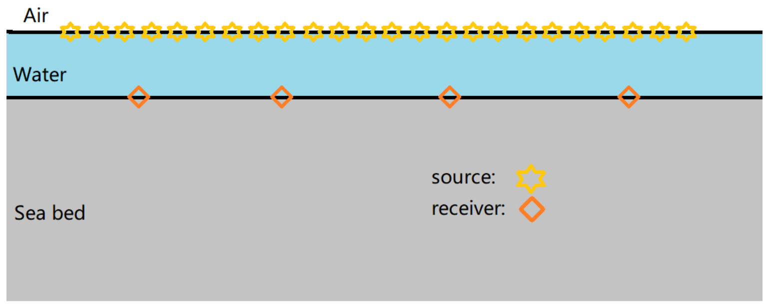


FIG. 1. Ocean bottom node acquisition has more shots than receivers

root (DSR) equation to extrapolate wavefield. The final image can be extracted at zero-offset and zero-time. Meanwhile, shot-profile migration extrapolate upgoing and downgoing wavefields separately. And the final image can be extracted by crosscorrelating two wavefields with image conditions.

For geometries with large numbers of shots (such as OBN), shot-profile migration like RTM is a more attractive choice, especially when the dimensionality of the problem can be reduced by common-azimuth (Biondi and Palacharla, 1996) or offset-plane wave (Mosher et al., 1997) approximations.

A significant improvement in imaging OBN data using RTM migration can be made using the reciprocity principle. Since receivers and sources can be switched through the reciprocity principle, the number of finite-difference simulations required for RTM can be reduced significantly. The principle of reciprocity illustrates that the source and receiver's location can be exchanged, and the same waveform will be observed (Claerbout, 1985). That is based on the reciprocity of ray tracing. As a result, the travel time is constant before and after exchanging the source and receiver. The validity of reciprocity is relatively simple to understand if all waves are scalar phenomena with scalar sources and scalar receivers. For instance, the explosive source and pressure-sensitive receivers generate acoustic pressure wave fulfills the scalar requirements, which is common in marine surveys like airgun and hydrophone. This principle becomes less valid when directional sources and receivers are involved. This report will only work with PP waves, but we will attempt to address the PS case in future work.

Blended acquisition

A suitable method to reduce OBN costs is to employ blended acquisition. While conventional acquisitions record energy coming from only one source at a time, blended acquisitions record energy coming from multiple sources simultaneously, as shown in Figure 2 (Garottu, 1983; Beasley et al., 1998; Berkhout, 2008). We call the shot record of blended acquisition "supershot." Compared with the traditional acquisition method, blending acquisitions can save time and achieve denser shot density. On the other hand, seismic processing normally requires unblended shot records, so deblending with different methods (Berkhout, 2008; Mahdad et al., 2011; Akerberg et al., 2008; Beasley, 2008; Abma and Yan, 2009) was introduced to separate supershots into single shots.

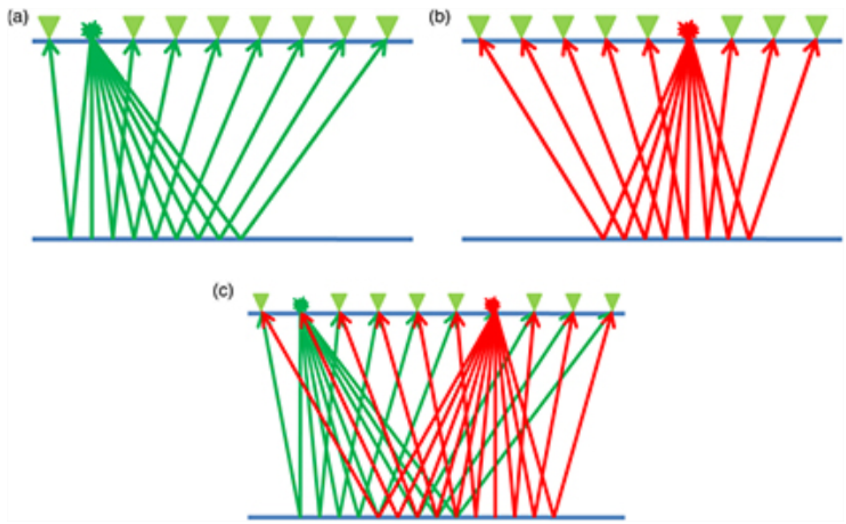


FIG. 2. (a) and (b) are illustrations of conventional single shot acquisition and (c) is blended shot acquisition.

Even if we can migrate blended data, separate source data is needed for processing steps such as denoising, static corrections, velocity analysis, and amplitude versus offset (AVO) analysis. We can separate shots using the difference in the apex locations of different source reflections. However, this approach's issue is that it is difficult to determine which event belongs to which shot gather.

To facilitate deblending, often shots are fired with some random time delay between them (Berkhout et al., 2009; Mahdad et al., 2011). The existence of several shot locations for each trace implies that each trace has multiple sets of offsets, azimuths, shot statics, and time delays, as shown in Figure 3. Simultaneous source data (also called blended data) can be synthesized from the non-overlapping (conventional) sources data by the following equation

$$b = \Gamma D \tag{1}$$

where b is the blended data, D represents the non-overlapping sources data cube, and Γ is the blending operator representing the sources firing times (Berkhout, 2008). Blended data b can be separated using the adjoint operator of the blending operator (called pseudo-deblending operator)

$$D' = \Gamma^T b \tag{2}$$

where D' is the pseudo-deblended data cube.

For shots with time delays, it is possible to separate blended shots by converting from the shot domain to other domains. Unless the time delays are removed, seismic events are incoherent across traces that contain different shots (and therefore different time delays). For example, this happens in the midpoint, receiver, common offset, azimuth vectors, and offset domains. For unblended acquisition, shot record shares a similar shape in the shot domain, midpoint domain, and receiver domain, as shown in Figure 4. But in dithered blended data, target shots turn coherent in midpoint domain(Hampson et al., 2008; Huo et al., 2012; Mahdad et al., 2011) and receiver domain, as shown in Figure 5. For each

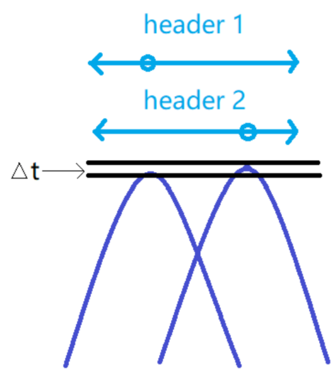


FIG. 3. Information for deblending includes multiple sets of headers and time delay between sources

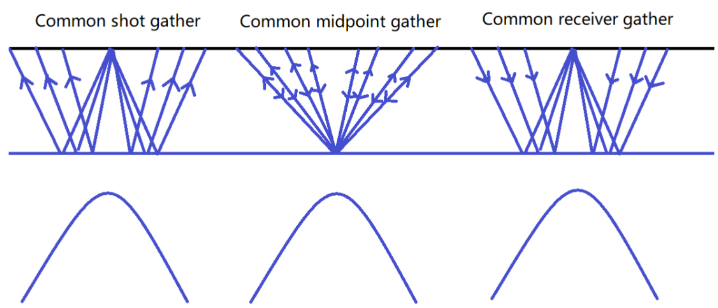


FIG. 4. Unblended acquisition in shot domain, midpoint domain and receiver domain

target shot in one supershot, there's a set of dithering time delay. Consequently, the size of the data increases by n_{blend} times, where n_{blend} is the number of sources simultaneously. Acquiring with a time delay as shown in Figure 3, we could remove this delay for each shot inside the "supershots." The target shot that sets the delay time is the shot we want to separate, and all the other shots are unwanted noise. In that way, we dither each shot record in the shot domain and add zero paddings for the blank. After dithering, the target shot turns coherent while all the other shots remain incoherent in the receiver domain because delay time only fits with the target shot.

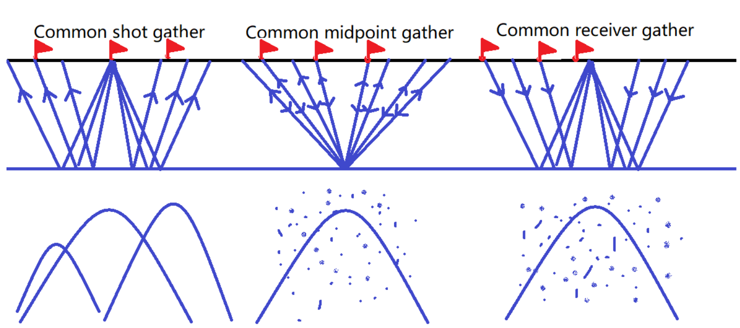


FIG. 5. Blended acquisition in the shot domain, midpoint domain, and receiver domain. The red flags are the source locations

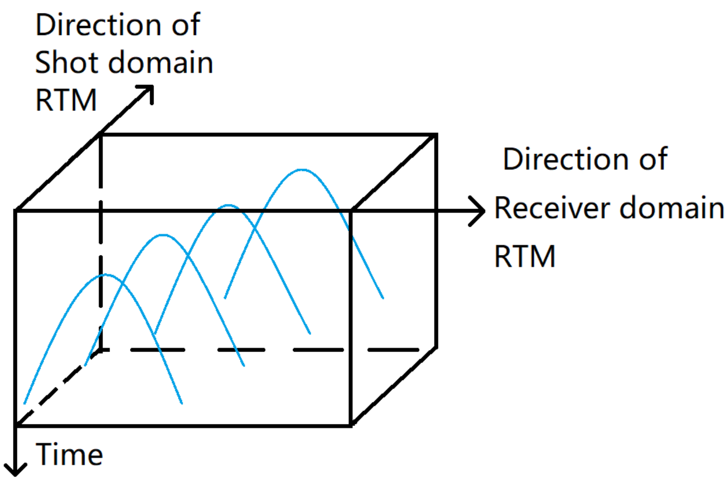


FIG. 6. Migration direction for shot domain RTM and receiver domain RTM

Deblending using RTM

RTM is a migration method that is based on the two-way wave equation. Compared with migration methods based on the one-way wave equation, RTM has better results for complex structures like salt structures. RTM is initially introduced by many authors (Baysal et al., 1983; Whitmore, 2005; McMECHAN, 1983). The computational time of RTM migration of OBN data increases since the forward/backward modeling is linearly related to the number of shots. It is significantly more efficient to migrate in the receiver domain. Utilizing the reciprocity of seismogram, we can exchange the location of shots and receivers, and the calculation time becomes linear in the number of receivers, as shown in Figure 6. The next problem to consider is how does dithering works in receiver domain RTM.

The concept of deblending by migration/demigration is that Green functions can act as basis functions onto which we can decompose the seismic data, independently of whether data are blended or not (Trad, 2018). In previous work, this has been done with Stolt operators (Trad et al., 2012; Ibrahim and Sacchi, 2015), but in those cases, the basis functions were more akin to apex shifted hyperbolas that represent true scatter responses. In deblending by migration, we map the blended data to their true location since RTM can naturally handle simultaneous shots. The cross-correlation imaging condition automatically deblends blended energy. Although some crosstalk remains, that can be taken care of using least-squares reverse time migration (LSRTM). Therefore, the blended energy is mapped to the correct reflector model, which can be used to predict the data to any arbitrary acquisition geometry, as it has also been done for data regularization (Trad, 2015). Demigrating the estimated RTM image to individual shots rather than supershots produces the unblended data. The quality of deblending and migration is related to the incoherency of blending interferences in the common receiver domain. The incoherency of the blending interferences is related to the randomness (dithering) of the shots.

METHOD

Deblending OBN data using RTM in common receiver domain

In this proposal, we start investigating two problems related to OBN surveys. First, we address RTM in the receiver domain with the sole purpose of saving computation time. Although this probably is done often in industrial settings, it does not seem to be discussed in publications. Second, we investigate how to deblend shots from the receiver gathers using migration/demigration techniques. Since nodes are fixed, the cost of OBN can be substantially reduced if many ships can fire simultaneously, creating a dense shot grid. We do not assume that migration/demigration techniques are the best option to deblend OBN surveys, but we believe it is an interesting option since the complexity of OBN data may be naturally handled by Green functions as opposed to parametric transforms like Fourier or Radon transforms.

The shot domain RTM for blended data is quite simple to implement. The backward wavefield is created as usual by injecting the blended data, but the forward wavefield is created by simultaneous injection of multiple sources with respective time delays. The cross-correlation of forward wavefield and backward wavefields is done as usual on each supershot and sum together.

There are multiple methods to implement receiver domain RTM. The size of data in the receiver domain is $n_{blended}$ times larger than the original data along the shot dimension, so by running the migration for each receiver gather, we pay no computing penalty since the number of traces for the backward field does not affect the computing time. Therefore, in blended receiver domain RTM, we just run a forward/backward propagation for each receiver. The random delays are applied for each shot inside a supershot as expected. There are two options: we can remove the dithering by time-shifting the whole data and the injection point or keep the original shift in regular blended RTM.

For the application of dithering in receiver domain RTM, during forward modeling, the random time delay (known) in shot causes different apex location of each shot inside the supershot. After dithering based on the time delays of the target shot, the start time of the target shot should be zero in all locations. So in the forward wavefield of source propagation, there's no time delay for source wavelet injection in receiver domain RTM, which the opposite of shot domain RTM. For the backward wavefield, the dithered data is injected. For dithering data, only the target shot is coherent, while all other shots are incoherent. So the corresponding shot wavefield only fits with the target shot, and the stacking of their cross-correlations strengthens the result. In contrast, all other incoherent data do not fit with the forward wave propagation, and cross-correlations get weak after summation.

Deblending OBN data using RTM in common offset and angle domains

As shown in Figure 3, in simultaneous acquisition data the use of multiple shot locations makes each trace to have multiple sets of shot dependent spatial coordinates, such as offsets and azimuths. Therefore, for different shots inside supershots, only the target shot

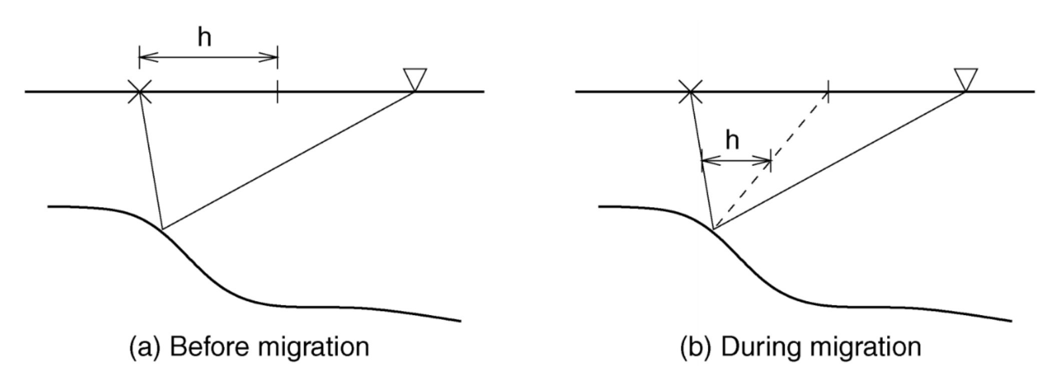


FIG. 7. Offset at surface and subsurface

has the correct header and time shift for the corresponding seismic data. After transforming the blended seismic data in common shot gather to offset, and angle domain common image gathers by the correct header of target shots, the other unwanted shots in the same supershots will be attenuated because their offset and ray trace angle are incorrect. Offset domain common image gather (ODCIG) and angle domain common image gather (ADCIG) means seismic images sorted by the offset and the incidence angle at the reflection point. Common-image gathers are an important output of prestack depth migration. They can provide a velocity model for depth migration and provide amplitude and phase information for subsequent subsurface attribute interpretation.

The computation of angle-dependent reflectivity is created by a wave-equation migration algorithm (De Bruin et al., 1990). Angle domain common image gathers can be extracted from shot-geophone migration in the offset-midpoint domain. These two methods are based on the wave equation, so there's no sensitivity to the ray-traced angle.

One thing that needs to be clear is that offset no longer means the distance between a shot and a receiver at the surface. Instead, offset means the subsurface offset between upgoing and downgoing wavefields. This is because in downward propagation wavefield, the offset between the two wavefields decreases as the depth increases for each reflection point as shown in Figure 7. So offset changes from a data-space parameter to a model-space parameter by migration.

One method for extracting ADCIG during RTM is utilizing Poynting vector(Dickens and Winbow, 2011).

The Poynting vector represents the directional energy flux of an wavefield(Stratton, 2007). The Poyning vector computation in seismic wavefield is

$$\mathbf{S} = -vP = -\nabla P \frac{dP}{dt} P \tag{3}$$

where $\mathbf{S}$ is the Poynting vector, $-v$ is the velocity vector and P is the stress wavefield(Cerveny, 2005). The $\mathbf{S}$ shares the same direction with the ray trace, so the angle between $\mathbf{S}_{source}$ and $\mathbf{S}_{receivers}$ is twice the value of reflection value.

$$cos2\theta = \frac{\mathbf{S}_{source}\mathbf{S}_{receivers}}{|\mathbf{S}_{source}||\mathbf{S}_{receivers}|} \tag{4}$$

where θ is the reflection angle. so the θ is

$$\theta = \frac{1}{2} arccos \frac{\mathbf{S}_{source}\mathbf{S}_{receivers}}{|\mathbf{S}_{source}||\mathbf{S}_{receivers}|} \tag{5}$$

and vector perpendicular to the reflection plane is

$$\mathbf{S} = (\mathbf{S}_{source} + \mathbf{S}_{receivers})/|cos2\theta| \tag{6}$$

The azimuth can also be computed, and in the 2D case, it is either $0°$ or $180°$. With the information of angles, the common angle gather can be obtained after RTM without external computation. The results of normal RTM is the cross-correlation of shot wavefield and receiver wavefield. It is the summation of all angle gathers. To get the common angle gathered, RTM's image condition shall include a reflection angle θ.

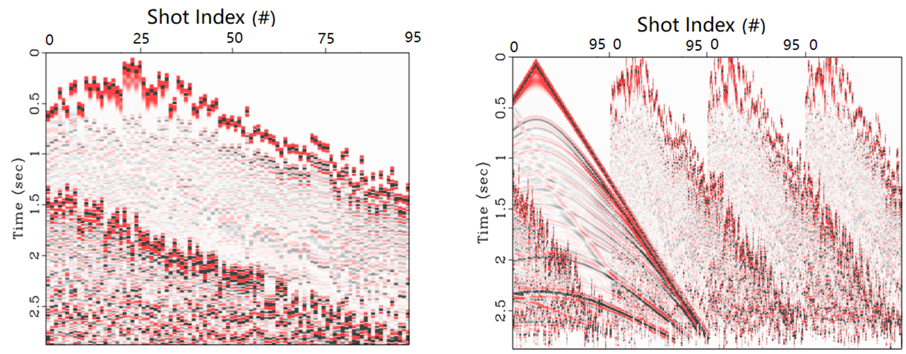
RESULTS AND DISCUSSION

RTM deblending in common receiver gather

In Figure 8, the left Figure shows a blended common receiver gather before pseudo-deblending. Because of the random time we introduced in Figure 3, the events are incoherent. The Figure on the right shows the blended common receiver gather before pseudo-deblending. There are four shots inside one "supershot," so pseudo deblending will expand the data space four times . The next step is dithering/shifting the shot slices. According to the four shots, we have four sets of random times. After correcting for each of them during the dithering process, the corresponding shot becomes coherent. It can be seen from the right Figure that only the shot whose delay was properly corrected for appears coherent, while the other three shots do not since they were not shifted by the right time delay.

For unblended acquisition, there should not be a difference between shot domain RTM and receiver domain RTM. We test this with a two-layered velocity model, with a geometry of 97 sources and five receivers evenly distributed on the top of the surface. We used a 4th-order finite-difference method for wave propagation. Two results are shown in Figure 9. After subtracting the two migration results, we see only a slight difference, apparently due to a shot footprint. The shot domain RTM takes nearly 20 times longer than the receiver domain RTM. For blended data and dithering, it is not obvious to us to answer by pure logic if results should be identical or not. Therefore, we try to answer this question by experimenting with the same velocity model as before. Simultaneous sources are simulated with four shots per supershot. We use five receivers on the surface. If the number of shots in time remains the same as the previous case, the number of shots increases four times. As a result, the new shot interval is one-fourth of the non-blended case. The results shown in Figure 10 look noisier compared with the unblended results in Figure 9. This is unclear at the moment of writing this report.

Comparing results of shot and receiver domain RTM as shown in Figure 10 we see they are very similar. The only difference is the shot footprint on the top of the image, but again the receiver domain RTM is much faster since the geometry contains less receiver than shots. In shot domain RTM, the cross-correlation of forward and backward wavefields need



a) Common receiver gather/CRG of blended data

b) CRG of blended data after pseudo-deblending (extend size nblend times and apply time shifting)

FIG. 8. a) is the common receiver gather of blended data and b) is after pseudo-deblending

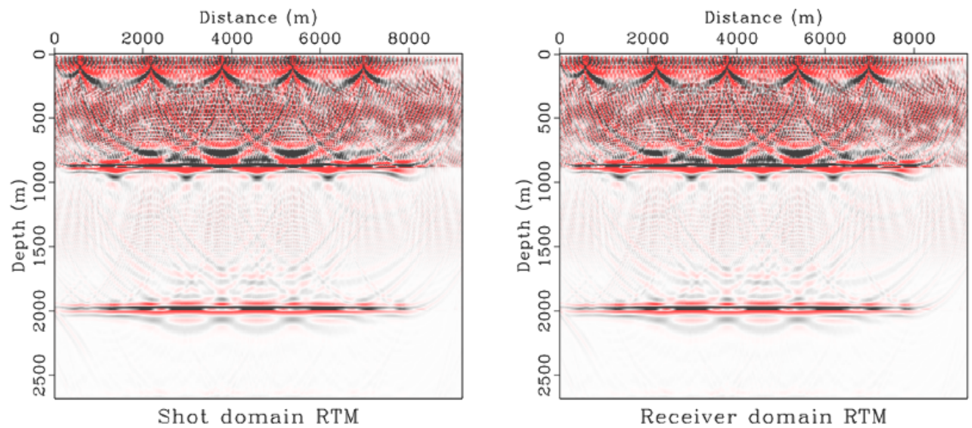


FIG. 9. Results of shot domain RTM and receiver domain RTM for a two-layer model

to be computed 95 times, which is the number of shots on time array, while on the receiver domain the cross-correlation only executes 20 times, which is the number of receivers. However, the main factor is the number of forward modeling operations required in one and the other case. For blended data, the computation in the shot domain is only 5 times larger than that in the receiver domain RTM, since blended shots are simultaneously injected.

As shown in Figure 11, we add a water layer on top of the Marmousi model and simulate an OBN survey. Then we migrate the data with RTM in the two domains. Like the acquisition system in a two-layered model, 95×4 shots and five receivers are distributed evenly on the water surface. The results of shot and receiver domain RTM are shown in Figure 12.

Results for the shot and receiver domain RTM are nearly the same. Similar to the results of the two-layered model, the only difference is the shot footprint. Again for this acquisition, the computation of shot domain RTM is five times larger than that in receiver domain RTM, and image qualities remain the same.

CONCLUSIONS

For some acquisition methods like OBN that have more shots than receivers, a migration method like RTM, whose cost is proportional to the number of shots, becomes compu-

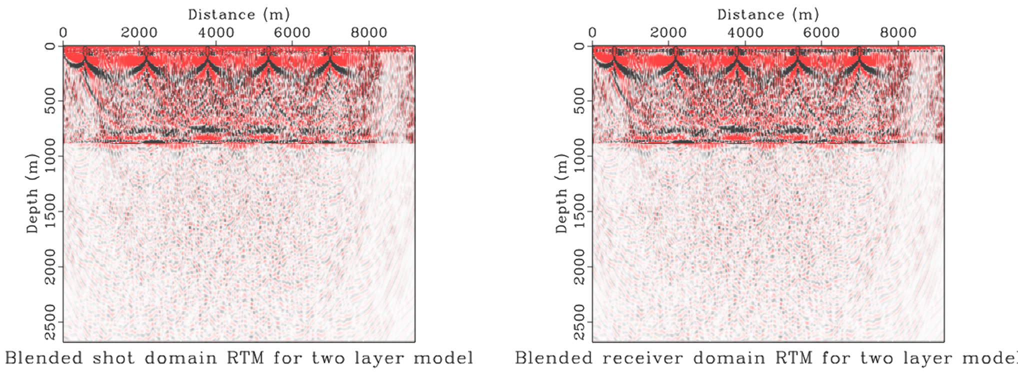


FIG. 10. Shot and receiver domain RTM from blended data

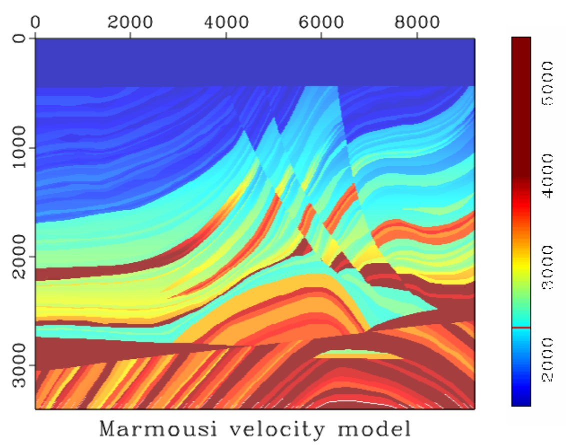


FIG. 11. Marmousi model with water layer on the top

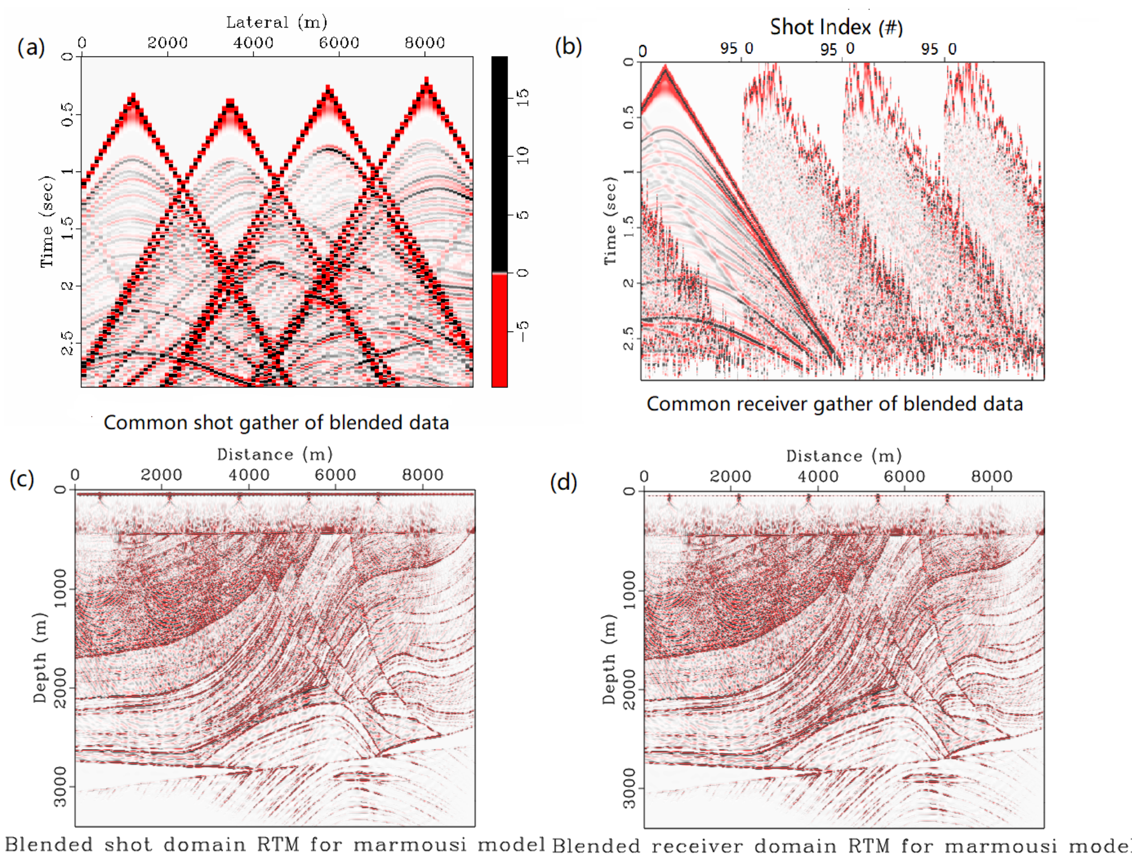


FIG. 12. (a) is the blended shot in a shot domain, (b) is the blended shot record in a receiver domain, (c) is the result of shot domain RTM from blended data and (d) is the result of receiver domain RTM from blended data

tationally expensive. In these cases, it is better to use receiver domain techniques than shot domain methods. This can be done by using the reciprocity principle. In addition, the high acquisition cost of OBN surveys can be mitigated by blended acquisitions. In this report we have explored the combination of both ideas, RTM and deblending, and performed a deblending-migration approach. RTM in common offset and angle domains also could be applied for deblending, and will be the topic of future reports.

FUTURE WORK

Least-squares migration

RTM uses an adjoint operator to approximate the inverse of the forward modeling(Claerbout, 1992), which is not a good approximation for the inverse operator. Lailly (1983) introduced the concept of least-squares migration (LSM). Instead of simply using the adjoint migration operator, in LSM the inverse process is sought by attempting to match the data predicted by the model with the observed data. LSM can approximate the inversion operator through either an iterative inversion(Tarantola, 2005; Schuster, 1993; Nemeth et al., 1999) or a single iterative inversion (Rickett, 2003). Moreover, LSM could recover some of the drawbacks of the incomplete seismic data like limited recording aperture, coarse sampling, and acquisition gaps(Nemeth et al., 1999), which is extremely suitable for OBN data. For blended acquisition, the multi-source LSRTM could suppress migration artifacts in the migration image and remove most of the crosstalk noise from multi-source data(Dai et al., 2010). So I will apply LSRTM for blended OBN data in the common receiver and common angle gather.

Elastic RTM

Seismic usually applies acoustic wave equations, which presume that earth only propagates compression waves. Although acceptable in practice, this assumption invalid theoretically. Shear wave can be detected at seismic sources and surfaces where compression wave converts. Conventional acoustic waves equation migration ignores S waves, which can result in the incorrect characterization of wave propagation, incomplete illumination of the subsurface, and poor amplitude characterization.

In contrast with the conventional marine acquisition, which could only record P waves, the OBN survey can receive both P and S waves from the seabed geophones. With the seismic data's help containing P and S waves, we could apply elastic migration methods like PP and PS wave RTM to compute elastic rock properties for geophysics interpretation.

Traditionally, offset domain common image gather are utilized in migration velocity analysis (MVA) and amplitude variation to offset studies (AVO) because zero offset image lack relevant information. However, ODCIG has the potential of image failure because of the ambiguity of image points, which can be a result of reflected energy multipathing. Signals from two or more subsurface locations can be recorded at the same seismic event in the data. To solve the reïňĆector ambiguity, angle domain imaging is introduced.

The main uses of images constructed using extended imaging conditions are MVA and

AVA analysis. However, such analyses require that images be decomposed corresponding to various angles of incidence, a procedure often referred to as angle decomposition. Angle decomposition takes different forms, corresponding to the type of wavefields involved in imaging. Thus, we can distinguish angle decomposition for scalar/acoustic and vector/elastic wavefields. For blended acquisition, different shots should also be able to separate using angle decomposition. With the help of the Poynting vector, we could extract ADCIG during RTM with little computation cost.

3D applications

Despite the high cost, the 3D seismic survey has many advantages compared with conventional 2D. The 3D seismic acquisition provides a volume of closely spaced seismic data in three dimensions. In contrast, the 2D seismic survey provides a slice of data in two dimensions. So 3D has a wider field coverage than 2D. Moreover, 3D seismic survey enhances the signal to noise ratio (S/N) significantly (Gaarenstroom, 1984).

In the 2D seismic acquisition, the data is 3D: time, receiver coordinates, and shots coordinates. We could deblend blended shots by transfer data from the shots domain to other domains like the receiver domain, offset domain, and angle domain. The target shot will be coherent, while other shots will be incoherent. However, in a 3D seismic survey, there are five dimensions to represent data in minimum space: inline, crossline, offset, azimuth, and time (other parameterizations are also possible) (Trad, 2008). Deblending through multiple domain transform is difficult because different domains are connected through complex physics. Nevertheless, I believe changing domains will make shots other shots incoherent since only the target shot has the correct header and time shift.

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