Multi-source least-squares migration of marine data

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SUMMARY

Kirchhoff based multi-source least-squares migration (MSLSM) is applied to marine streamer data. To suppress the crosstalk noise from the excitation of multiple sources, a dynamic encoding function (including both time-shifts and polarity changes) is applied to the receiver side traces. Results show that the MSLSM images are of better quality than the standard Kirchhoff migration and reverse time migration images; moreover, the migration artifacts are reduced and image resolution is significantly improved. The computational cost of MSLSM is about the same as conventional least-squares migration, but its IO cost is significantly decreased.

INTRODUCTION

It has been shown that least-squares migration (LSM) (Nemeth et al., 1999; Duquet et al., 2000) can improve the resolution of the migration images and suppress the migration artifacts. However, one of the drawbacks of LSM is its high computational cost. Romero et al. (2000) proposed a blended source method by encoding and stacking different shot gathers into a supergather. The blended source data was formed by phase encoding each shot gather and stacking the shot gathers together to get a supergather. Dai et al. (2011) adapted LSM to blended source data, which I now define as the multi-source least-squares migration (MSLSM) procedure. This algorithm is applicable to Kirchhoff migration (Dai et al., 2011), wave-equation migration (Huang and Schuster, 2011) and reverse time migration (Dai et al., 2010). Schuster et al. (2011) provide rigorous formulas for predicting the level of crosstalk noise as a function of the encoding parameters .

Application of wave equation MSLSM to marine streamer data is hampered by the mismatch between the extensive number of live traces computed by a finite-difference algorithm and the limited number of traces recorded in the field. This leads to severe residuals in the misfit function, and therefore strong artifacts. However, this problem does not exist for Kirchhoff based MSLSM, which can be applied to marine streamer data without any restrictions on the acquisition geometry.

THEORY

The phase-encoded multi-source data (i.e., supergather) can be represented as (Dai et al., 2011)

$$\mathbf{d} = \sum_{i=1}^{S} \mathbf{P}_i \mathbf{d}_i, \qquad (1)$$

where $\mathbf{d}$ is an M×1 vector defined as the supergather data, $\mathbf{d}_i$ is the M×1 vector for the ith shot gather, S is the number of shots, and the M×1 matrix $\mathbf{P}_i$ represents the phase-encoding function. It is typically a scaled identity matrix, where the scaling function is proportional to $e^{i\omega\tau}$ for the traces shifted by τ (Schuster et al., 2011). The $\mathbf{P}_i$ can also account for a random polarity value of ± 1. It is shown in Schuster et al. (2011) that the combination of random polarity changes and random time shifts is more effective at reducing crosstalk noise than using each of them alone. Each trace of the supergather is a superposition of traces from a number of shots, which introduces the crosstalk noise. A receiver-side phase-encoding function is applied to each trace of the shot gathers with different recording apertures to form a supergather. Since the recording aperture is known, these shot gathers can be decoded correctly.

We assume that the ith CSG $\mathbf{d}_i$ and the reflectivity model $\mathbf{m}$ are related by

$$\mathbf{d}_i = \mathbf{L}_i \mathbf{m}, \qquad (2)$$

where $\mathbf{L}_i$ is the linear forward modeling operator associated with the ith shot. Plugging equation (2) into (1), we get

$$\mathbf{d} = \sum_{i=1}^{S} \mathbf{P}_i \mathbf{L}_i \mathbf{m} = \mathbf{L}\mathbf{m}, \qquad (3)$$

where the supergather modeling operator is defined as

$$\mathbf{L} = \sum_{i=1}^{S} \mathbf{P}_i \mathbf{L}_i. \qquad (4)$$

Multi-source migration

From equation (4), the supergather migration operator is defined as the adjoint of the supergather modeling operator,

$$\mathbf{L}^T = \sum_{i=1}^{S} \mathbf{L}_i^T \mathbf{P}_i^T. \qquad (5)$$

Figure 1 depicts key steps for applying multi-source Kirchhoff migration to marine streamer data. Two distinct shot gathers with different recording apertures (Figure 1a) are first phase-encoded (Figure 1b) then stacked to generate a supergather (Figure 1c). In Kirchhoff migration, each trace is decoded for the correct shot and receiver locations before migration. For example, if a trace is encoded by time shift of 1 s, then that trace is decoded by a -1 s time shift (Figure 1d). In Figure 1e, the event in the blue solid circle is smeared to the model space (solid blue ellipse) from the associated source and receiver of CSG1, while the event in the red solid circle from associated source and receiver of CSG2. Events with dashed line are smeared along the dashed ellipse. Therefore, the solid

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lines indicate the migration artifacts and the dashed lines indicate the crosstalk noise. The supergather migration image is

$$\begin{aligned}
\mathbf{m}_{mig} &= \mathbf{L}^T\mathbf{d} = \mathbf{L}^T\sum_{i=1}^{S}\mathbf{P}_i\mathbf{L}_i\mathbf{m} \\
&= \sum_{j=1}^{S}\mathbf{L}_j^T\mathbf{P}_j^T\sum_{i=1}^{S}\mathbf{P}_i\mathbf{L}_i\mathbf{m} \\
&= \sum_{i=1}^{S}\sum_{j=1}^{S}\mathbf{L}_j^T\mathbf{P}_j^T\mathbf{P}_i\mathbf{L}_i\mathbf{m} \\
&= \overbrace{\sum_{i=1}^{S}\mathbf{L}_i^T\mathbf{L}_i\mathbf{m}}^{standard\ mig} + \overbrace{\sum_{j\neq i}\sum_{i=1}^{S}\mathbf{L}_j^T\mathbf{P}_j^T\mathbf{P}_i\mathbf{L}_i\mathbf{m}}^{crosstalk}, \qquad (6)
\end{aligned}$$

consisting of two terms: the first term is the standard migration image and the second term is the crosstalk noise introduced by multi-source blending of shot gathers. The magnitude of the crosstalk term for a variety of different encoding functions is derived in Schuster et al. (2011).

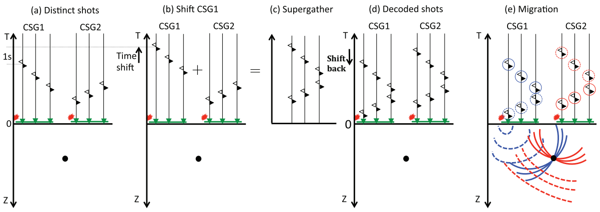

Figure 1: Illustration of steps for multi-source Kirchhoff migration. (a) shows single shot CSGs with a marine streamer acquisition aperture, receiver positions are different for each shot, (b) shows phase-encoding which shifts CSG1 1 s later, (c) shows the supergather data generated by stacking traces from CSG1 and CSG2, (d) shows the decoded shot gathers, where the supergather trace is shifted back by 1 s and (e) shows the migration of the decoded CSGs with the associated source and receiver positions.

Multi-source least-squares migration

To suppress crosstalk noise, we find the optimal $\mathbf{m}$ by minimizing the objective function

$$f(\mathbf{m}) = \frac{1}{2}||\mathbf{d}-\mathbf{L}\mathbf{m}||^2 + \frac{1}{2}\lambda||\mathbf{m}-\mathbf{m}_{apr}||^2. \qquad (7)$$

The second term is the regularization functional (Tikhonov and Arsenin, 1977), and λ is the damping parameter. The optimal model $\mathbf{m}$ can be found by a gradient type optimization method

$$\mathbf{m}^{(k+1)} = \mathbf{m}^{(k)} - \alpha\mathbf{F}(\mathbf{L}^T(\mathbf{L}\mathbf{m}^{(k)}-\mathbf{d})+\lambda\mathbf{m}^{(k)}), \qquad (8)$$

where $\mathbf{L}^T(\mathbf{L}\mathbf{m}^{(k)}-\mathbf{d})+\lambda\mathbf{m}^{(k)}$ is the gradient, $\mathbf{F}$ is a preconditioning matrix and α is the step length. As both the forward modeling and migration operators are linear and adjoint to each other, the analytical step length formula can be used. Alternatively, in order to improve the robustness of the MSLSM algorithm, a quadratic line search method is carried out with the current model and two trial models. Wang and Schuster (2011) shows that dynamic encoding (change the encoding function for each iteration) achieves the best image quality but at the highest IO cost. Static encoding (keep the encoding function the same for all iterations) incurs the least IO cost but suffers from more crosstalk noise. The computational and IO performance of hybrid encoding (reset encoding function every few iterations) lies in between. In this study, we use the steepest descent (SD) method with dynamic encoding.

NUMERICAL RESULTS

The Kirchhoff-based MSLSM algorithm is tested on a marine data set. The goal is to compare the quality of the MSLSM against that of the KM and RTM images.

There are 496 shots with a shot interval of 12.5 m, and the streamer length is 6 km with a receiver interval of 12.5 m. A 10-15-70-75 Hz bandpass filter is applied to the raw data, and the source wavelet is estimated by stacking the near-offset ocean-bottom reflections. The P-velocity model is estimated from full waveform inversion. Thirty two supergathers are generated from a total of 496 shot gathers, and each supergather consists of 15 or 16 blended shots. Random polarity and time-shift encoding (a zeros-mean normal distribution with a standard variation of σ=0.5 s) are applied to each trace.

Figure 2 (a) - (d) shows the standard Kirchhoff migration image, reverse time migration image, least-squares migration image after 30 iterations, and multi-source least-squares migration image with dynamic encoding after 30 iterations. Two detailed areas (solid and dashed at the same position for all 4 images) are shown in Figures 3 and 4. These results shows that LSM can achieve better image quality with significantly higher resolution compared to standard Kirchhoff migration and reverse time migration. MSLSM can achieve the same quality image after 30 iterations but with one-fifteenth IO cost.

DISCUSSION AND CONCLUSION

A multi-source least-squares migration algorithm is proposed to efficiently produce high quality images. Receiver-side and source-side phase-encoding function are used to generate the supergathers. Field results show that both LSM and MSLSM can decrease migration artifacts, balance the amplitudes and increase the image resolution. Compared with single source LSM, MSLSM can significantly decrease the IO cost and memory cost, but not the CPU cost. Numerical results also suggest that dynamic encoding achieves the best image quality but at the highest IO cost. Applying this method to 3D GOM data is now an active line of research.

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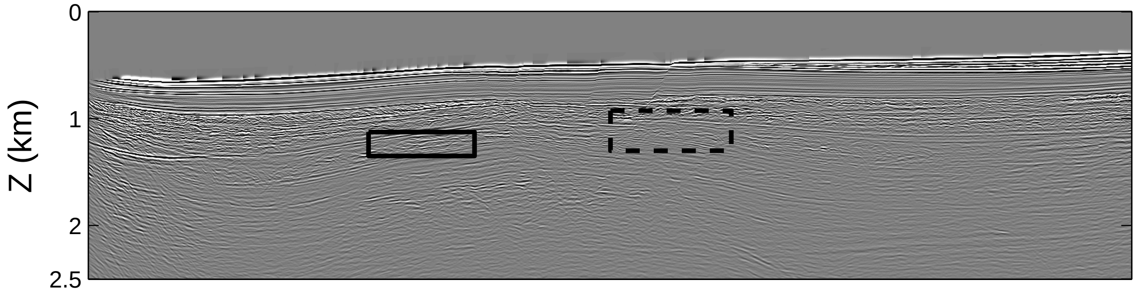
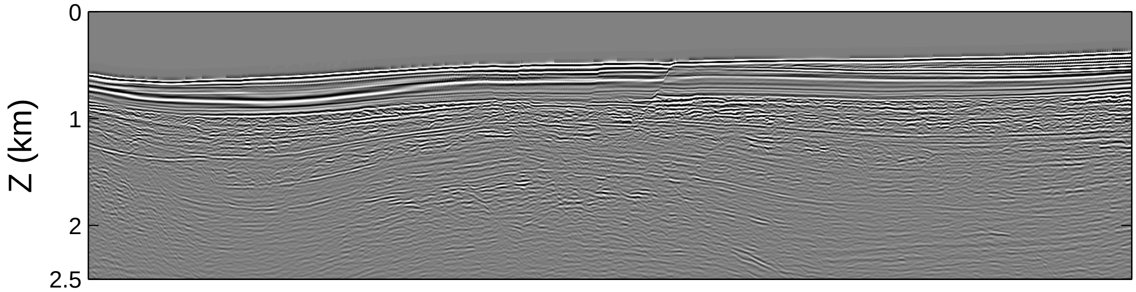
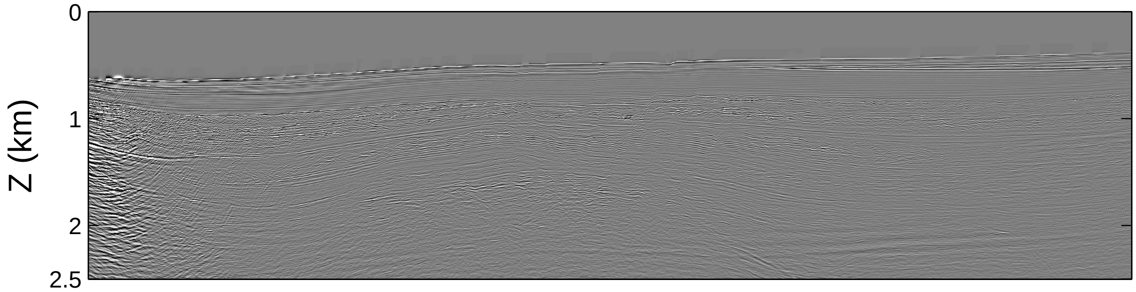


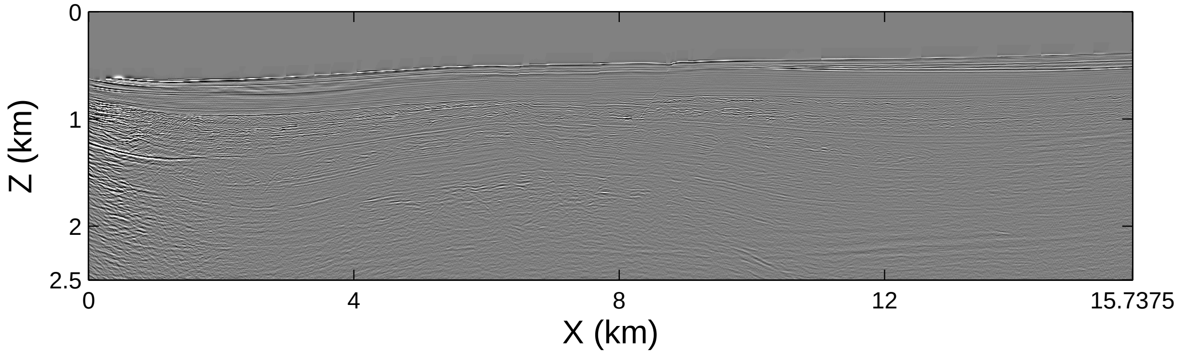
(a) Kirchhoff Migration Image



(b) Reverse Time Migration Image



(c) Least−squares Migration Image after 30 Iterations



(d) Multi−source LSM Image after 30 Iterations

Figure 2: Images of (a) standard Kirchhoff migration, (b) reverse time migration, (c) least-squares migration, and (d) multi-source least-squares migration with dynamic encoding. Two boxes (solid and dashed) in (a) indicates the same areas for zoom view from all 4 images.

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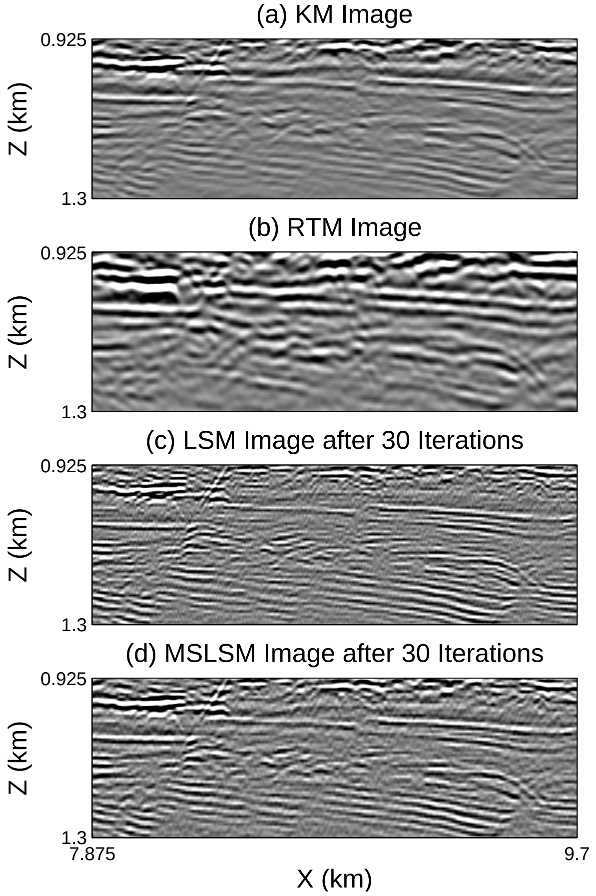

Figure 3: Zoom view of solid box in Figure 2. (a)-(d) show the zoom view of KM, RTM, LSM and dynamic encoding MSLSM images.

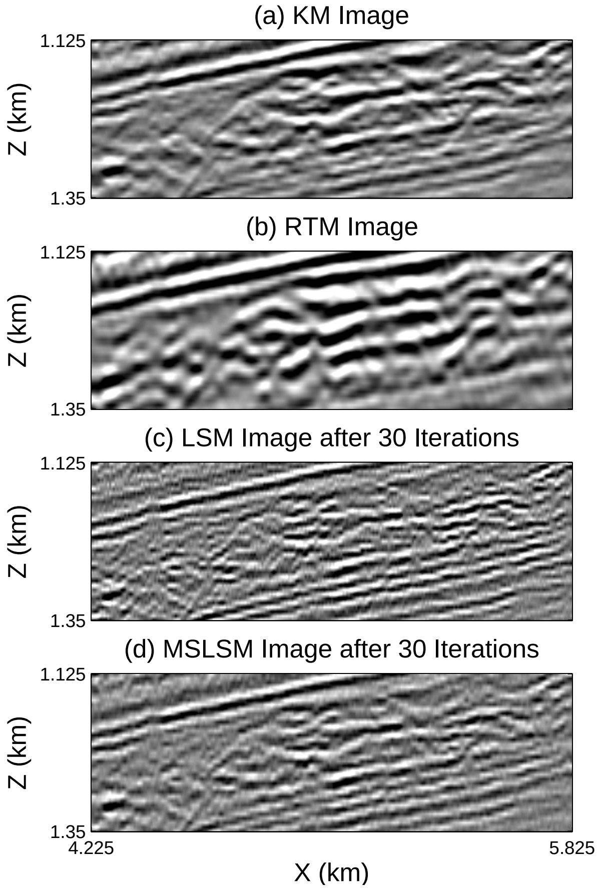

Figure 4: Zoom view of dashed box in Figure 2. (a)-(d) show the KM, RTM, LSM and dynamic encoding MSLSM images.

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EDITED REFERENCES

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