Report 5

3-D PRESTACK WAVEPATH MIGRATION

Hongchuan Sun

ABSTRACT

As a reduced form of Kirchhoff migration (KM), wavepath migration (WM) was developed for the purpose of reducing computational costs as well as suppressing far-field migration artifacts. This goal was partly achieved in 2-D migration, showing that WM was able to increase the image resolution, suppress migration artifacts, and was 4-11 times faster than KM. However, for a few complex data events, imaging by WM led to reduced S/N than KM. In this report, WM is applied to both synthetic and field 3-D prestack data sets. The results with synthetic data show that WM can give rise to fewer migration artifacts and can sometimes define complex structure better than KM. The results with field data show that WM can mostly suppress migration artifacts and can sometimes resolve the reflection interfaces better than KM. The CPU comparison shows that, for synthetic data examples, WM can be more than an order-of-magnitude faster than KM, and for the field data example, WM can be approximately an order-of-magnitude faster than KM. The limitation of 3-D WM is that it is sometimes less robust than KM because of its sensitivity to recording geometry in estimating the incidence angles of the reflections.

INTRODUCTION

In 3-D KM, seismic events in a trace are smeared along quasi-ellipsoids. For a cubic velocity model and a dense recording geometry with $N$ grid points along one side, the migration of a single trace requires a computational count of $O(N^3)$. For 3-D iterative velocity analysis, this could be a huge burden in CPU requirements. In
addition, strong far-field migration artifacts can be generated as the trace energy is migrated to positions far away from the actual reflection point.

To rectify these problems, we formulated a less costly alternative denoted as WM (Sun and Schuster, 1998, 1999a). The migration aperture of WM is not the entire quasi-ellipsoid, but is localized to a small portion of it, which is called the migration Fresnel zone. Typically, the volume of the Fresnel zones for migrating a single trace should be less than $O(N^{1.5})$, so that, the computational cost of WM could be considerably less than that of KM.

The WM algorithm was formerly tested on 2-D synthetic and field data sets (Sun, 1999b, 1999c), and was shown to, in some examples, suppress migration artifacts, increase the image resolution, and resolve complex structure better than KM. It was also shown that 2-D prestack WM can be 4-11 times faster than 2-D prestack KM. However, this computational efficiency was typically achieved when a slant-stack technique was used to subsample the data. It is highly expected that, for a 3-D geometry, WM can be an order-of-magnitude faster than KM without subsampling the data, and further, can be two orders-of-magnitude faster than KM if the data are subsampled.

In this report, WM is applied to three 3-D prestack data sets: synthetic data associated with a point scatterer model, synthetic data associated with the SEG/EAGE Salt model, and West Texas field data. The key objectives of this report are to determine whether 3-D WM can create images of comparable or better quality than 3-D KM, and to assess the computational efficiency of 3-D WM compared to 3-D KM.

NUMERICAL RESULTS

Point Scatterer Model

The WM algorithm is first tested on a simple 3-D model, where a buried point scatterer is centered below the geophone configuration at a depth of 500 m. Receivers are uniformly distributed on a 26x26 orthogonal grid with a grid interval of 40 m. The source is a 50 Hz Ricker wavelet; the medium velocity is homogeneous with $c = 4000$ m/s; the time sampling interval is 2.0 ms; and the model is represented by a 51x51x51 grid with a grid-point spacing of 20 m in the x, y, and z directions. A 3-D diffraction-stack-forward-modeling method is used to generate the synthetic seismograms, where geometric spreading has been included.

Figure 5.1 shows the KM images at different depth levels. The point scatterer is well resolved in the KM image at the depth of 500 m, but at the depths of 320 m, 480 m, and 660 m, the migration artifacts are clearly seen. In contrast, the WM image in Figure 5.2 shows better image fidelity at the point scatterer level, and the energy leakage away from the point scatterer level is less than that of KM. As noted in our previous papers, the WM reduces aliasing artifacts by not smearing energy far from its specular reflection area.
SEG/EAGE Salt Model

The WM algorithm is now tested on a more realistic prestack data set, the phase B synthetic data associated with the SEG/EAGE 3-D Salt model. The data set contains 169 shots of marine streamer traces with 65 groups per streamer. The group interval is 40 m, the near offset is 160 m, and the far offset is 2760 m. The sample interval is 8.0 ms, and the recording time is 5.0 s. The data set has a storage size of approximately 150 Mbytes. Figure 5.3 shows one of the common shot gathers (CSG) after direct wave removal, and the related model parameters are given in Table 1.

Table 1. The parameters for the SEG/EAGE 3-D salt model. Here the model is discretized into a \((N_x, N_y, N_z)\) grid, with grid intervals of \((dx, dy, dz)\). The travel-time field is gridded into a \((N_{xt}, N_{yt}, N_{zt})\) grid, with grid intervals of \((dxt, dyt, dzt)\).

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Figure 5.4 shows a crossline section of the 3-D velocity model, Figure 5.5 shows the prestack KM image, and Figure 5.6 shows the prestack WM image for the same crossline. In the migration, all of the traces were used to construct the image at any subsurface point. Compared to the KM image in Figure 5.5, the WM image contains fewer migration artifacts, and more clearly defines the complex salt boundary. Figure 5.7 shows another WM image except with 1/6 subsampled data applied to the migration. Compared to Figure 5.6, Figure 5.7 contains more artifacts, and shows worse reflection signals, but still describes the salt boundary clearly. However, the computational cost has been significantly decreased. Thus, there is a trade-off in image quality and computational costs. The zoom views of Figure 5.4-7 are shown in Figure 5.8 for a detailed view of this trade-off in quality.

Figure 5.9 shows an inline section of the 3-D velocity model, Figure 5.10 shows the prestack KM image, and Figure 5.11 shows the prestack WM image for the same inline. Compared to the KM image in Figure 5.10, the WM image shows a clearer salt boundary, and contains fewer migration artifacts. However, the interface continuity for some of the reflections are worse than in the KM image. Compared to Figure 5.11, the 1/6 subsampled WM image in Figure 5.12 contains more artifacts and shows narrower image coverage, but still resolves the salt boundary clearly. Figure 5.13 depicts the zoom views of the inline images, where the velocity model is also shown.

Figure 5.14 presents the horizontal image slices at the depth of 1400 m. The true velocity model is shown in Figure 5.14b, where the complex salt boundary dominates the section. The WM image in Figure 5.14c correlates well with the true structure, but the KM image in Figure 5.14a shows a blurred salt boundary and contains more migration artifacts. Compared to Figure 5.14c, the 1/6 subsampled WM image in
Figure 5.14d loses some image quality, but still defines the complex structure better than KM.

Figure 5.15 shows the horizontal image slices at the depth of 1880 m, where the true velocity model is also shown. The WM image in Figure 5.15c resolves the salt boundary well. In contrast, the KM image in Figure 5.15a contains more migration artifacts, and can not resolve some of the structural details. Compared to Figure 5.15c, the 1/6 subsampled WM image in Figure 5.15d loses some image quality, but still correlates well with the true structure.

The CPU comparison shows that WM is 33 times faster than KM, and the subsampled WM is 170 times faster than KM. For field data, the computational efficiency might not be so high, but we are still encouraged by these synthetic data results.

**West Texas Field Data**

The WM algorithm is finally tested on a 3-D land data set, the West Texas prestack data. The 500 Mbyte data set contains 328 shots for a total of 138,000 traces. The receiver inline and crossline spacings are 67 m and 402 m, respectively. The sample interval is 4.0 ms, and the recording time is 3.4 s. Table 2 shows the related model parameters.

Table 2. The model parameters for the West Texas data. Here the model is gridded into a \((N_x, N_y, N_z)\) grid, with grid intervals of \((dx, dy, dz)\). The traveltime field is gridded into a \((N_{xt}, N_{yt}, N_{zt})\) grid, with grid intervals of \((dxt, dyt, dzt)\).

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Figure 5.16 shows one of the common shot gathers (CSG), where the S/N ratio of the data is pretty low. Figure 5.17 shows the associated recording geometry of the CSG in Figure 5.16. Notice that the receiver inline spacing is unchanged, and the receiver crossline spacing is constant except for an inline line with a pointed arrow. This irregularity will not cause any inconvenience in implementing KM. However, large errors could be created for WM in estimating the incidence angles of the reflections when the source-receiver geometry is irregular. A possible remedy for this problem is to interpolate the traces such that the receiver distribution is regular. We conveniently choose the simple way by muting out the traces on the irregular inline line. As a result, about 20,000 traces were not used in the migration. Figure 5.18 shows the new recording geometry of the CSG in Figure 5.16.

Figure 5.19 shows an inline section of the prestack KM image, and Figure 5.20 shows the associated prestack WM image. In the migration, a total of 118,000 traces
were used to construct the image at any subsurface point. Compared to the KM image in Figure 5.19, the WM image shows clearer reflection signals and contains fewer migration artifacts. Figure 5.21 shows another WM image except a 1/2 subsampled data was used with a narrower migration Fresnel zone applied in the migration. Compared to Figure 5.20, the subsampled WM image in Figure 5.21 loses some image quality, but still defines reflection events similar to the KM image.

Figure 5.22 shows a crossline section of the prestack KM image, and Figure 5.23 shows a prestack WM image for the same crossline. Compared to the KM image in Figure 5.22, the WM image contains fewer migration artifacts, and resolves the interfaces noticeably better. Compared to Figure 5.23, the subsampled WM image in Figure 5.24 contains more migration artifacts, and shows worse signal continuity. However, the computational costs have been significantly decreased.

Figure 5.25 shows the horizontal image slices at the depth of 2481 m. Compared to the KM image, the WM images contain fewer migration artifacts, and show better image resolution.

The CPU comparison shows that WM is 14 times faster than KM, and the subsampled WM is 50 times faster than KM. For marine data, whose receiver distribution is usually regular, the computational efficiency and quality of WM could be higher. The reason is that, for a regular recording geometry, the incidence angles can be computed more accurately. As a result, the data can be further subsampled, and the size of the migration Fresnel zone can be further decreased. Notice that we have assumed a trade-off between image quality and the associated computational costs.

**DISCUSSION**

The 3-D WM algorithm was applied to both synthetic and field prestack data. Results with the point scatterer data show that WM can increase the image resolution and reduce the energy leakage away from the scatterer point. Applying WM to the SEG/EAGE synthetic data shows that WM can give rise to fewer migration artifacts, and define the complex salt boundary more accurately than KM. Applying WM to the West Texas field data shows that WM can suppress the migration artifacts and resolve the reflection interfaces noticeably better than KM.

The CPU comparisons show that WM is 33 times faster than KM for the SEG/EAGE synthetic data, and is 14 times faster than KM for the West Texas field data. The computational efficiency of WM can be further increased by subsampling the data, reducing the size of the migration Fresnel zone, and by migrating fewer seismic events in a trace. Subsampling sometimes yields an acceptable decrease in image quality for a much higher gain in computational efficiency.

The WM algorithm can deal with many different recording geometries, but it prefers a regular receiver distribution in order to more easily compute incidence angle. For a land data set with irregular receiver distribution, trace interpolation is
recommended for an accurate calculation of the incidence angles.

Future work will apply WM to 3-D marine field data, and search for the optimal rules in slant stacking and interpolating the traces. Finally, WM will be applied to 3-D iterative velocity analysis.

ACKNOWLEDGEMENTS

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REFERENCES


Sun, H., 1999c, 2-D prestack wavepath migration applied to the Husky data: Univ. of Utah Tomography and Modeling/Migration Development Project, 1999 Midyear Report, 41-50.
Figure 5.1: 3-D prestack KM image sections at different depths for a buried point scatterer, where a 26x26 grid of traces is generated with a 50 Hz Ricker wavelet source. The point scatterer is centered below the geophone configuration at a depth of 500 m.
Figure 5.2: Same as previous figure except the WM images. Notice that the migration artifacts have been visibly attenuated compared to the KM images.
Figure 5.3: A CSG associated with the SEG/EAGE 3-D Salt model, where the direct waves have been removed.
Figure 5.4: A crossline (X,233) velocity section of the SEG/EAGE 3-D salt model.

Figure 5.5: Crossline (X,233) section of the 3-D prestack KM image. A full aperture KM method was used to construct this image. The associated velocity model is shown in Figure 5.4.
Figure 5.6: Same as Figure 5.5 except the WM image. Compared to the KM image in Figure 5.5, this image contains fewer migration artifacts, and delineates the top boundary of the salt more clearly. However, the signal strength is lower than that of the KM image for part of the salt bottom and for some of the reflection interfaces.

Figure 5.7: Same WM image as Figure 5.6 except with 1/6 subsampled data applied in the migration. At the same time of speeding up the algorithm, more migration artifacts are created, but the salt boundary is still well resolved.
Figure 5.8: Zoom views of the previous crossline sections for the (a) KM image, (b) associated velocity model, (c) WM image and (d) subsampled WM image. Compared to the KM image in (a), the WM images in (c) and (d) contain fewer migration artifacts, and correlate well with the true structure.
Figure 5.9: An inline (109,Y) velocity section of the SEG/EAGE 3-D salt model.

Figure 5.10: Inline (109,Y) section of the 3-D prestack KM image. A full aperture KM method was used to construct this image. The associated velocity model is shown in Figure 5.9.
Figure 5.11: Same as Figure 5.10 except the WM image. Compared to the KM image in Figure 5.10, this image contains fewer migration artifacts, and shows the salt boundary more clearly. In addition, at very deep depths, WM resolves the reflection interfaces somewhat better than KM. However, WM has lost some of the weaker interfaces which are very close to the salt boundary.

Figure 5.12: Same WM image as Figure 5.11 except with 1/6 subsampled data applied in the migration. Here the salt boundary is still clearly resolved, but the events are weaker, and the image coverage is narrower because of the sparse recording geometry. However, the computational costs have been greatly reduced.
Figure 5.13: Zoom views of the previous inline sections for the (a) KM image, (b) associated velocity model, (c) WM image, and (d) subsampled WM image. Compared to the KM image in (a), the WM images in (c) and (d) contain fewer migration artifacts, and accurately describe the salt boundary.
Figure 5.14: Horizontal slices at the depth of 1400 m for the (a) KM image, (b) associated velocity model, (c) WM image, and (d) subsampled WM image. The WM images in (c) and (d) contain fewer migration artifacts, and resolve the salt boundary clearly. In contrast, the KM image in (a) shows a blurred salt boundary.
Figure 5.15: Horizontal slices at the depth of 1880 m for the (a) KM image, (b) associated velocity structure, (c) WM image, and (d) subsampled WM image. Compared to the KM image in (a), the WM images in (c) and (d) contain fewer migration artifacts, and correlate well with the true structure.
Figure 5.16: A CSG of the West Texas field data, where inline trace interval is 67 m and the crossline trace interval is 402 m.
Figure 5.17: The recording geometry of the CSG shown in Figure 5.16. Notice that the arrow-marked inline is shifted away from its regular position.

Figure 5.18: Same as previous figure except that the irregular inline receivers have been removed. This recording geometry will be used in both the KM and the WM algorithms.
Figure 5.19: An inline section of the 3-D prestack KM image. A full aperture KM method was used to construct this image.

Figure 5.20: Same as Figure 5.19 except the WM image. Compared to the KM image in Figure 5.19, this image contains fewer migration artifacts, and resolves the reflection interfaces noticeably better.
Figure 5.21: Same WM image as in Figure 5.20 except that 1/2 subsampled data was used in the migration. Here the reflection interfaces are acceptably resolved, but the events are weaker and more noise was created.
Figure 5.22: A crossline section of the 3-D prestack KM image. The data are heavily aliased in the source and receiver crossline directions, and so the aliasing artifacts are present in the image.

Figure 5.23: Same as Figure 5.22 except the WM image. Compared to the KM image in Figure 5.22, this image contains fewer migration artifacts, and resolves the reflection interfaces somewhat better.
Figure 5.24: Same WM image as in Figure 5.23 except with 1/2 subsampled data used in the migration. Here the events are weaker, and more noise was created. This is mostly because the data coverage is too coarse along the crossline direction.
Figure 5.25: Horizontal slices at the depth of 2481 m for the (a) KM image, (b) WM image and (c) subsampled WM image. The WM images in (b) and (c) contain fewer migration artifacts, and show better image resolution.