Illumination from 3D imaging of multiples: an analysis in the angle domain

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Summary

Angle domain common image gathers provide information for velocity model building and amplitude versus angle (AVA) analysis. They require good angular illumination to deliver reliable results. The main acquisition parameter affecting angular illumination is the shot density, which can be coarse in conventional marine towed-streamer acquisition. Imaging of multiples can help mitigate the problem, as it employs the down-going wavefield as an areal source. The areal source augments source density when compared with the point source used for imaging of primaries. We apply Separated Wavefield Imaging (SWIM) to create angle domain common image gathers from sea surface-related multiples. Imaging of multiples improves the angle gathers in the coarser sampled direction, e.g. 90-degree azimuth. We demonstrate these concepts by using a wide azimuth (WAZ) field data example.

Introduction

In exploration geophysics, both primaries and multiples can be used for depth imaging. Conventional wave equation migration extrapolates up-coming boundary data generated from primary reflection to image the subsurface. Separated wavefield imaging propagates up and down-going wavefield and constructs images using sea surface-related multiples. This is feasible after effective wavefield separation being applied to generate up-going and down-going wavefields.

The use of sea surface-related multiples for depth migration has been discussed by Berkhout and Verschuur (1994), Guitton (2002) and Whitmore et al. (2010). Compared to imaging of primaries, 3D imaging of sea surface-related multiples can enhance subsurface illumination especially for areas not well imaged by primaries. Lu et al. (2011) present a 3D example (SEAM synthetic) comparing the imaging using multiples with imaging using primaries for a wide azimuth towed-streamer acquisition survey, where the image from multiples enhances dirty salt illumination. Lu et al. (2013) discuss the capability of the technology when applied to 3D field data examples. In the shallow water scenario, imaging of multiples mitigates strong acquisition footprint and generates very high-resolution images. The enhanced subsurface illumination from imaging of multiples can potentially help to reduce drilling hazards risks.

When compared to imaging of primaries, imaging of multiples increases the subsurface illumination coverage. This is because imaging of multiples uses down-going wavefield as an areal source, which is broadly distributed on the surface compared to the point source used in imaging of primaries. Figure 1A demonstrates how imaging of multiples illuminates a larger subsurface region (dashed circles) than imaging of primaries (solid circles).

More significantly, imaging of multiples enhances the angular illumination of a point in the subsurface. Figure 1B shows the reflection angles from imaging using one-shot of primaries and multiples. The diagram illustrates how at a single subsurface location, imaging of primaries can only have one reflection angle; while imaging of multiples can produce more than one reflection angle even when using only one shot.

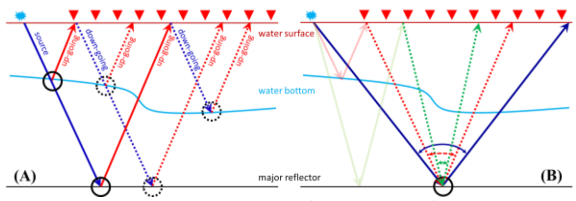

Figure 1: (A) Schematic diagram for imaging of primaries (solid lines) and imaging of multiples (dashed lines). Illumination from multiples (dashed circles) covers greater subsurface extent than illumination from primaries (solid circles). (B) At a single subsurface reflector (solid circle), there is a single reflection angle generated from imaging of primaries (solid lines); while there can be more than one reflection angles generated from imaging of multiples (dashed lines).

We use a 3D wide azimuth (WAZ) deep-water field data example to demonstrate the enhanced subsurface areal illumination and angular illumination from imaging of multiples. Angle gathers are generated from imaging of primaries and multiples. As expected, the multiples angle gathers prove to be denser and less affected by coarse source sampling than the primaries angle gathers. The finely sampled angle domain image gathers can be used for tomography and pre-stack post processing to improve the overall quality of depth migration.

Method

In shot profile wave equation migration, the imaging process is a combination of wavefield downward extrapolation and imaging condition (Claerbout, 1971). The conventional depth migration backward propagates the up-coming data as receiver wavefield and forward extrapolates a synthetic impulse wavelet as source wavefield. Imaging of multiples propagates up and down-going wavefields as receiver and source wavefields, where boundary data are generated at the receiver locations via up-down wavefield

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separation. We employ an extrapolation method based on a Fourier Finite Difference operator [Equation 1]. P is pressure wavefield; ω is temporal frequency; c is reference velocity; v is media velocity; $\nabla_{x,y}$ is spatial derivative; a and b are finite difference coefficients. The operator can simulate wavefield extrapolation in isotropic or anisotropic media (Valenciano et al. 2009), and can mimic wavefield propagation in acoustic or viscoacoustic media (Valenciano et al. 2011).

$$\frac{\partial P}{\partial z} = \pm i\left[\sqrt{\frac{\omega^2}{c^2}+\nabla^2_{x,y}}+\left(\frac{\omega}{v}-\frac{\omega}{c}\right)+\frac{\omega}{v}\left(1-\frac{c}{v}\right)\frac{\frac{v^2}{\omega^2}\nabla^2_{x,y}}{a+b\frac{v^2}{\omega^2}\nabla^2_{x,y}}\right]P \qquad (1)$$

An up/down imaging principle is applied at the subsurface. We use a stable version of deconvolution imaging condition (Guitton et al. 2007) to suppress the cross-talk generated from unrelated correlation of up and down-going wavefields. Subsurface images are generated in both the stacked and pre-stack domain.

$$I(\vec{x}) = \sum_{\vec{x}_s}\sum_{\omega}\frac{P_{up}(\vec{x}_s,\vec{x},\omega)P^*_{down}(\vec{x}_s,\vec{x},\omega)}{\left\langle P_{down}(\vec{x}_s,\vec{x},\omega)P^*_{down}(\vec{x}_s,\vec{x},\omega)\right\rangle_{\vec{x}}+\varepsilon(\vec{x},\omega)} \qquad (2)$$

$$I(\vec{x},\vec{h}) = \sum_{\vec{x}_s}\sum_{\omega}\frac{P_{up}(\vec{x}_s,\vec{x},\omega,\vec{x}+\vec{h})P^*_{down}(\vec{x}_s,\vec{x},\omega,\vec{x}-\vec{h})}{\left\langle P_{down}(\vec{x}_s,\vec{x},\omega,\vec{x}-\vec{h})P^*_{down}(\vec{x}_s,\vec{x},\omega,\vec{x}-\vec{h})\right\rangle_{\vec{x}}+\varepsilon(\vec{x},\omega)} \qquad (3)$$

In Equation 2 and 3, $I(\vec{x})$ is the subsurface stacked image in depth, $I(\vec{x},\vec{h})$ is the subsurface pre-stack image in the offset domain; h is the source receiver half offset; P_{up} and P_{down} are the up and down-going wavefields; ε is a damping parameter to make the deconvolution imaging condition stable; $\langle\ \rangle_{\vec{x}}$ stands for smoothing in the image space. Subsurface offset gathers can be converted to angle domain after applying a radial-trace transform (Rickett and Sava, 2002).

Images are generated shot by shot and are stacked to form a composite image after migration. The images from primaries and from multiples are created separately and can be combined after migration.

Example

We apply imaging of primaries and imaging of multiples to a 3D WAZ deep-water field data example. The subsurface area is anisotropic, and we employ TTI pre-stack depth migration. In this example, compared to imaging of primaries, imaging of multiples enhances subsurface areal illumination and angular illumination by using the extensively distributed down-going wavefield as the source wavefield.

In Figure 2, we compare subsurface illumination between imaging of primaries and imaging of multiples. The plots display a vertical section of the shooting direction. The spark and triangles at the surface display the shot receiver coverage (of a 2D section) of one shot. The grey scale images are from the full 3D survey: image of primaries (A) and image of multiples (B). The red-black areas indicate the images from using one-shot data. The one-shot image from multiples covers much broader subsurface region than the corresponding primaries image, which is demonstrated by the diagram in Figure 1A.

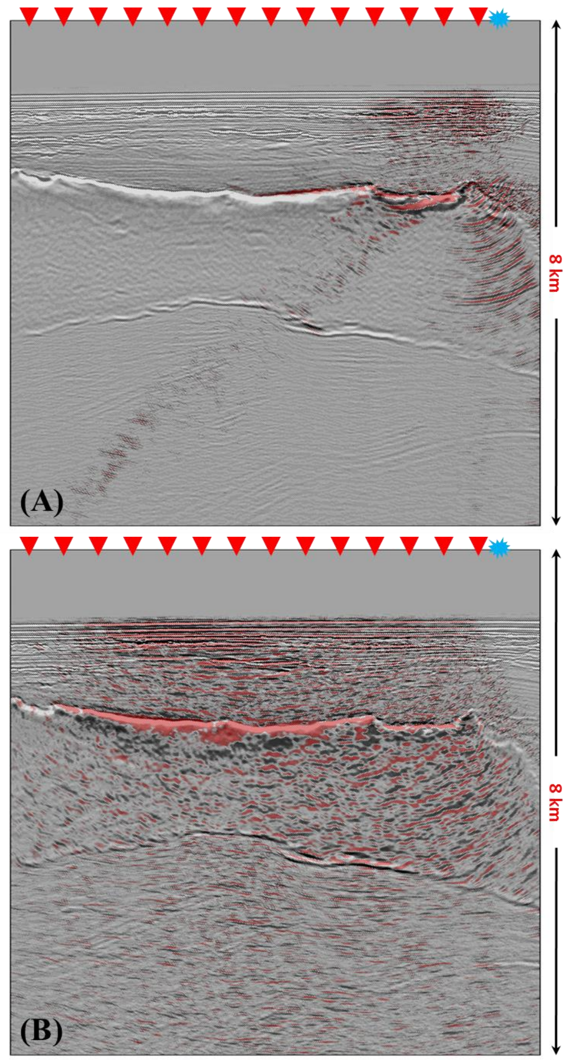

Figure 2: Images generated from one-shot data (color) on top of the stacked images (grey) from a 3D WAZ field data example. When using one-shot data, imaging of multiples (B) creates larger subsurface illumination coverage than imaging of primaries (A), which is consistent with Figure 1A.

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In Figure 3, depth slices at 3km below sea surface are compared between imaging of primaries and imaging of multiples (a 30km by 30km region from the full survey). At this depth, top salt boundaries are illuminated by both primaries and multiples. Inside the zoomed box, the image from multiples has a more continuous and clearer salt boundary than the image from primaries. Imaging of multiples enhances subsurface illumination especially when complex structures are present (e.g. salt bodies).

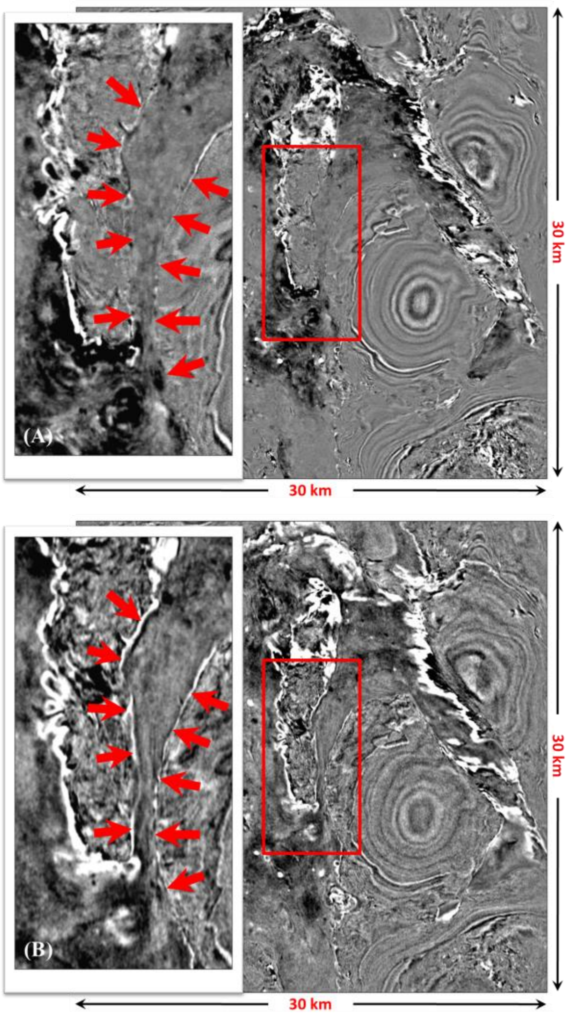

Figure 3: Depth slices (3km below sea surface) from imaging of primaries (A) and imaging of multiples (B). Imaging of multiples builds more continuous and clearer salt boundary reflection images than imaging of primaries (indicated by red arrows inside the zoomed region).

Imaging of multiples improves angular illumination. The angular illumination depends on shot density. In marine streamer acquisition, the shot separation in the cross-line direction is typically several hundred meters, which is insufficient for generating good quality angle gathers when imaging using primaries. Because the down-going wavefield acts as an areal source, the multiples have much denser "shot sampling" than primaries. Therefore, imaging of multiples generates much more finely sampled angle gathers than imaging of primaries, especially at the 90-degree azimuth direction when short spacing is large.

Figure 4A displays the vertical profile of inline image from imaging of multiples (0-8km from sea surface); and Figure 4B shows the corresponding 90-degree azimuth angle gathers (maximum angle range from -25 to +25 degrees). In both post-stack image and pre-stack angle domain images, multiples illuminate structures from shallow to subsalt regions. The complex structures of salt boundaries and salt inclusions are very well imaged in the post-stack image (4A), because imaging of multiples enhances pre-stack angular illumination (4B).

Figure 5 displays the zoomed view of angle gathers inside the red-box region in Figure 4B. The gathers are displayed in both inline (zero degree azimuth) and cross-line (90-degree azimuth) directions, maximum angle range from -70 to +70 degrees. Figure 5A shows angle gathers from primaries along the shooting direction (zero degree azimuth) and 5B displays the corresponding results from multiples. Zero degree azimuth angle gathers from imaging of multiples are more finely sampled than imaging of primaries. This is more obvious when at complex structures such as top salt, which is not as flat as shallow sediment and the reflection angles are difficult to be recovered in migration. The enhanced angular illumination from imaging of multiples contributes to the better salt boundary illumination in post-stack domain, which we have observed in Figure 3B. At the 90-degree azimuth direction, the angle illumination from imaging of primaries is more problematic. Figure 5C displays the angle gathers at 90-degree direction from imaging of primaries. There are only several sparsely distributed angles in this direction, due to the very large shot spacing (sailline spacing is equal to 600 meters). Imaging of multiples creates densely populated angle gathers in cross-line direction [Figure 5D], because the down-going wavefield is more finely sampled than a point source. In both imaging of primaries and imaging of multiples, the maximum angular coverage of inline direction is larger than the cross-line direction. This is because the streamer cable length is bigger than the cross-line acquisition spread.

Using this 3D WAZ field data example, we have demonstrated that imaging of multiples improves subsurface areal illumination and angular illumination. Imaging of multiples generates much clearer salt boundary images than imaging of primaries and angle gathers from

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imaging of multiples are much more finely sampled than the angle gathers from imaging of primaries.

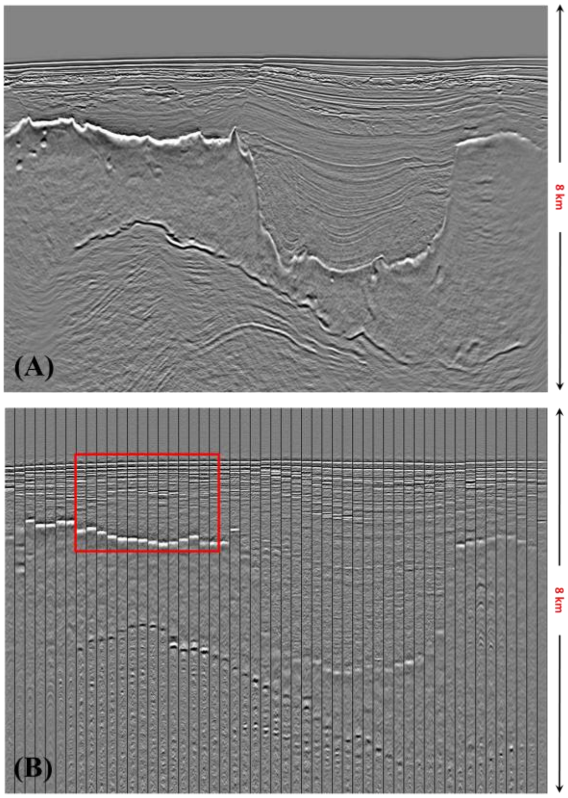

Figure 4: Vertical profile of inline image from multiples (A), and the angle gathers from multiples (B). The gathers are at the 90-degree azimuth direction, and maximum angle from -25 to +25 degrees.

Conclusions

We have applied Separated Wavefield Imaging (SWIM) for migration of sea surface-related multiples. The separated up and down-going wavefields are required as boundary data for imaging of multiples. A Fourier Finite Difference operator is used to propagate source and receiver wavefields to the subsurface. A deconvolution imaging condition is used to suppress the cross-talk and multiple noise. Subsurface images and image gathers are created from imaging of primaries and imaging of multiples. Imaging of multiples uses a densely populated areal source (down-going wavefield) and improves subsurface imaging coverage and angular illumination. Using a 3D WAZ field data example, we have demonstrated that imaging of multiples improves salt boundary illumination and creates more finely sampled angle gathers. The densely populated angle gathers can be used for velocity model building and for pre-stack post processing to improve overall quality of depth migration.

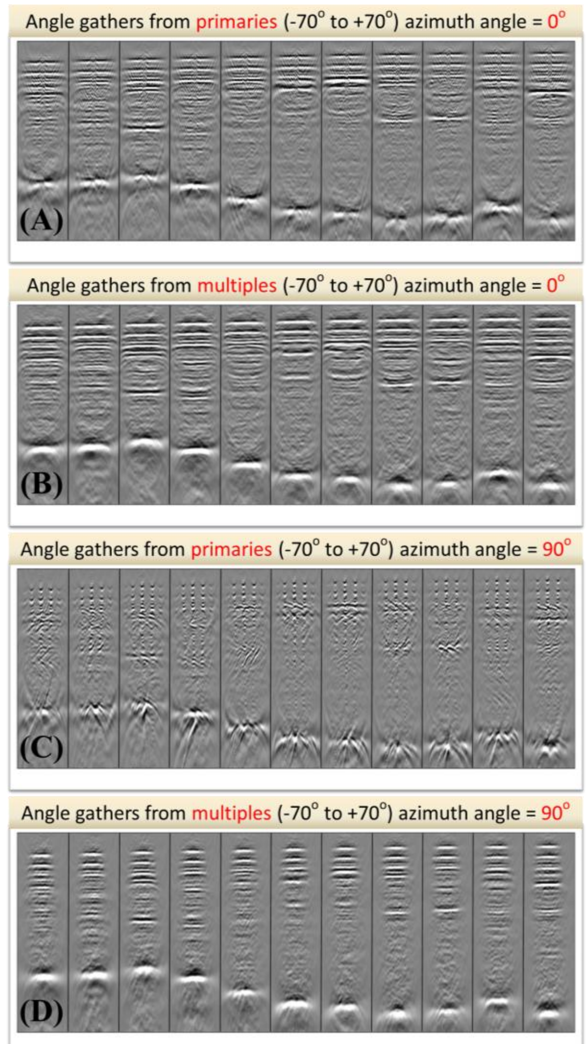

Figure 5: Angle gathers from imaging of primaries and imaging of multiples. The region corresponds to the red box area in Figure 4B. The gathers from imaging of primaries have illumination issues due to the coarse shot spacing, especially at the 90-degree azimuth direction in panel (C). Gathers from imaging of multiples (B, D) are finely sampled in both inline and cross-line directions.

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EDITED REFERENCES

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