Extending the 3D primary image with multiples and mirrors

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Summary

This presentation reviews imaging technologies applied to both primaries and multiples, with particular emphasis on the value of multiples in wide azimuth scenarios. Included is a discussion of imaging principles, extraction of offset and angle dependent measurements, and mitigation of crosstalk. Whether multiples are considered as a replacement for unrecorded primaries, or complementary (or redundant) measurements to primaries, a more complete image of the subsurface can be produced by including both primaries and multiples in the imaging process. In some cases, the multiples image is superior to the primaries.

Examples show the additional value multiples contribute in 3D wide azimuth scenarios: multi-streamer surface acquisition, ocean bottom seismic and 3D VSP's.

Included is a prognosis for future - including advances in imaging methods and the trade-offs of acquisition sampling (cost) and image quality.

Introduction

The goal of seismic imaging is to illuminate as much of the subsurface as possible. To achieve this goal, acquisition configurations have trended more and more towards some form of wide azimuth acquisition. The 3D wide azimuth scenarios discussed here include: multi-streamer marine, ocean bottom seismic (OBS) and 3D vertical seismic profiles (VSP). In marine streamer acquisition, there is a tradeoff between the number of streamers being towed and the density of shots and sail lines, where the number of receivers is typically significantly higher than the number of shots. On the other hand, in ocean bottom seismic or 3D vertical seismic profiles, the number of shots is much higher than the number of receivers. (See Figure 5)

For economic reasons, it is never the case where there are sources and receivers "everywhere" in any of these acquisition scenarios. As a consequence, the subsurface image from primaries may be incomplete and multiple scattering can be used as additional signal. Prior to imaging the total wavefield (primaries plus multiples) can be separated into up-going and down-going wavefields at the receiver positions. In the cases of 3D OBS or VSP, it is typical to invoke a reciprocity augment, mapping common receiver gathers into (reciprocal) common shot gathers. So, from an imaging point of view, data from wide azimuth acquisition scenarios (3D WAZ, OBC, VSP) can be viewed as "shot" seismograms with well sampled "receiver arrays". In the case of primaries, the down-going wavefield originates from an active (or blended) source. In the case of multiples, the down-going and up-going wavefields can be used as secondary "sources" along with receiver wavefields. Both wavefields are extrapolated and imaged (e.g. Berkhout and Verschuur, 1994, Whitmore, et al, 2010, Lu, et al, 2014).

One of the challenges in using multiply-scattered wavefields is the crosstalk in images of wavefields of different scattering order and interfaces. This crosstalk can be reduced through the estimation, imaging and adaptive subtraction (Lu, et al, 2016). Inversion based methods, including closed loop full wavefield imaging (Berkhout, 2012, 2014b; Davydenko and Verschuur, 2014) also mitigate crosstalk and can estimate the earth's reflectivity by iterative imaging of primaries, surface related and internal multiples. (See the Leading Edge, July 2015 for more references and a review of the use of multiples in imaging.)

Imaging Methodology – Shot migration framework:

The most basic imaging principle for either primaries or multiples include two basic steps: wavefield propagation of incident and reflected wavefields and application of an imaging principle. Two methods of wavefield propagation are depth extrapolation or modeling (as in RTM). Examples of imaging conditions include some form of cross-correlation or deconvolution of the extrapolated wavefields. A form of deconvolution imaging condition is:

$$I(\mathbf{x}) = \sum_{xs} \int \frac{D^*(\mathbf{x}, \mathbf{x}_S, \omega) U(\mathbf{x}, \mathbf{x}_S, \omega)}{\left\langle D^*(\mathbf{x}, \mathbf{x}_S, \omega) D(\mathbf{x}, \mathbf{x}_S, z, \omega) \right\rangle + \alpha(\mathbf{x}, \omega)} d\omega \; ; \mathbf{x} = (x, y, z) \quad (1)$$

Angle Gathers:

The imaging condition shown in equation 1 is the stacked image over all shots. This imaging condition can be applied to either primaries or surface multiples. This imaging principle can be extended to the pre-stack domain as indicated in equation 2, where **h** is the subsurface offset of the image.

$$I(\mathbf{x}, \mathbf{h}) = \sum_{xs} \int \frac{D^*(\mathbf{x} - \mathbf{h}, \mathbf{x}_S, \omega) U(\mathbf{x} + \mathbf{h}, \mathbf{x}_S, \omega)}{\left\langle D^*(\mathbf{x} - \mathbf{h}, \mathbf{x}_S, \omega) D(\mathbf{x} + \mathbf{h}, \mathbf{x}_S, z, \omega) \right\rangle + \alpha(\mathbf{x}, \omega)} d\omega \; ; \mathbf{x} = (x, y, z) \quad (2)$$

The subsurface offset gathers can then transformed to subsurface angle gathers through the angle to offset transformation (Sava and Fomel, 2003) as in equation (3).

$$\left.\begin{array}{l} A(\mathbf{x},\boldsymbol{\mu},z) = \int I(\mathbf{x}, z + \boldsymbol{\mu} \bullet \mathbf{h}, \mathbf{h}) d\mathbf{h} \\ \boldsymbol{\mu} = -\dfrac{\mathbf{k_h}}{k_z} \quad \mathbf{h} \quad \gamma = \tan^{-1}(-\dfrac{|\mathbf{k_h}|}{k_z}) = \textit{incident angle} \end{array}\right\} \quad (3)$$

It is also possible to generate angle gathers during imaging in reverse time migration by direct binning during the imaging process (Whitmore, et al 2014).

Angle gathers can be generated for both primaries and multiples. These gathers can subsequently be used for angle domain based processing and velocity estimation.

Crosstalk

In the ideal case, imaging primaries is achieved by extrapolating source and primary reflected wavefields. To achieve this goal it is typical to remove multiples before imaging. However, if multiple removal is not applied, then the up-going data contains both the primary and multiply scattered wavefields. The resultant "primary" image contains phantom images, which are crosstalk between the down-going source wavefield and the back propagated multiples wavefield. Standard processing methods avoid this by estimating and subtracting the multiples in the time (data) space. However, an equivalent result can be achieved by imaging the estimated multiples as causal crosstalk (resulting in phantom images deeper than true reflector). The crosstalk is then subtracted in the image space.

Surface related multiples can be migrated as signal by depth extrapolation and imaging of the down-going and up-going surface wavefields. However, in this case there are two types of crosstalk – causal (as in primaries) and anti-causal (which are phantom reflectors that precede the true reflectors). Both types of crosstalk can be estimated and subtracted (Lu, et al, 2016).

Examples

Figure 1 shows angle gathers for imaged multiples before and after crosstalk attenuation from a 3D dual-sensor multi-streamer survey acquired in the Barents Sea. The crosstalk was estimated, imaged and then adaptively subtracted from the crosstalk contaminated angle gathers.

Multiples can extend angular illumination beyond that obtained by primaries alone. Figure 2 shows crossline angle gathers for primaries and multiples from a Gulf of Mexico (GOM) wide azimuth survey. The sail line spacing is 600 meters, which is the source sampling in the crossline azimuth direction. However, the receiver cable spacing is much finer than the sail line spacing. Since the down-going wavefield is sampled at the receiver spacing, the angle gathers from the multiples provide superior angular illumination to the primaries in this azimuth direction.

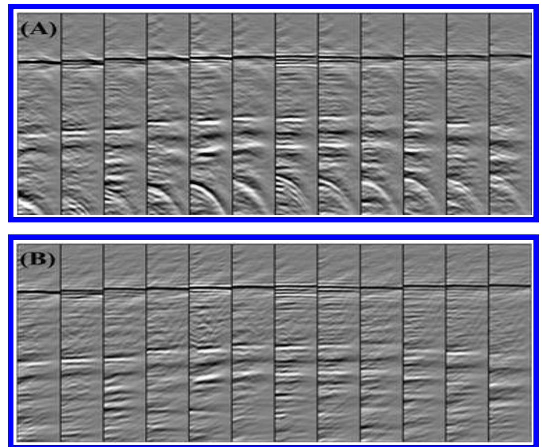

Figure 1 Barents Sea angle gathers from multiples, before crosstalk removal (A) and after crosstalk removal (B)

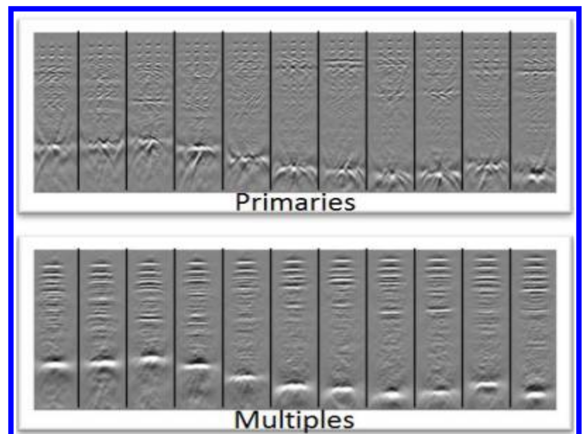

Figure 2. GOM Wide azimuth angle gathers from primaries and multiples with an azimuth 90 degrees from the sail line azimuth. Note the improved angular sampling of multiples.

In streamer WAZ imaging of multiples the down-going wavefield exists at the receiver locations, which then acts large areal source, which then can improve the subsurface illumination of multiples when compared to primaries.

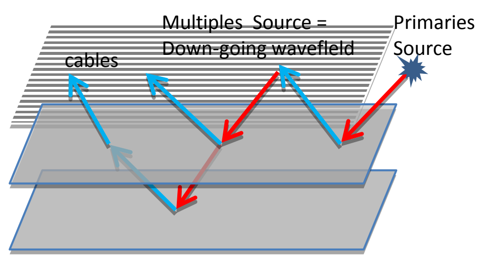

Figure 3. In WAZ acquisition the down-going wavefield in multiples act as a large areal array when compared to a "point" source used in the imaging of primaries.

Shown below is a comparison of the GOM wide azimuth depth slice image from primaries and multiples at a depth of 3km. Consistent with the observation of improved angular illumination of multiples in the crossline direction, we see superior images of the multiples over the primaries in much of this depth slice. There is improved imaging from the multiples at the top and flanks of salt.

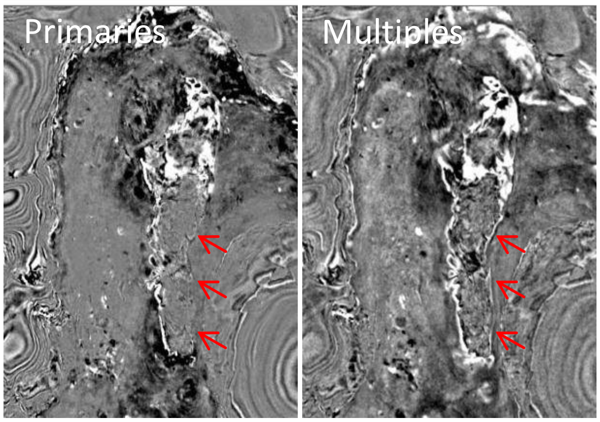

Figure 4. Depth slices at 3km of 3D wide azimuth stack for primaries and multiples. Superior images from multiples over primaries are indicated.

Multiples and Mirrors in OBS and VSP's

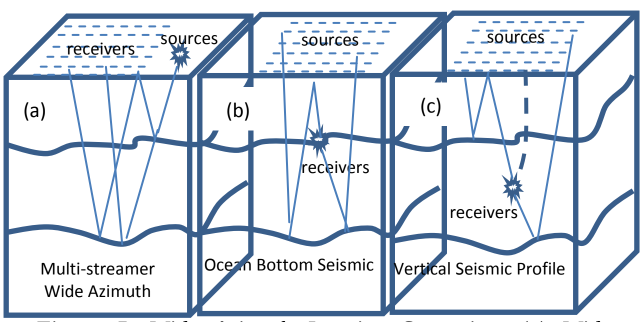

Figure 5. Wide Azimuth Imaging Scenarios: (a) Wide azimuth surface seismic (b) Ocean bottom seismic (c) 3D vertical seismic profiles.

In surface wide azimuth acquisition, the sources and receivers are near or at the surface. After basic processing (e.g. deghosting, wavefield separation, datuming), input to imaging is the up-going and down-going data at the surface. In OBS or 3D VSP acquisition the receivers are either at the seafloor (OBS) or deeper depth (VSP) (Figure 5). In preparation for imaging, the data recorded at the receivers is separated into down-going and up-going wavefields (Figure 6.)

Figure 6. Wavefield separation is used to separate the multi-component data into down and up-going wavefields, which with acoustic approximations, are imaged as compressional waves.

These recorded data are vector wavefields that could be imaged with an elastic imaging process. However, it is also common to restrict imaging methods to imaging of compressional waves. For the purpose of a shot migration framework, a reciprocity augment can be invoked, where common receiver gathers imaged as (reciprocal) common shot gathers.

In the OBS case, both the primaries and multiples can be imaged for both the up-going and down-going wavefields. Shown in Figure 7 are raypath diagrams for the different scenarios in imaging of OBS data. Because the down-going mirror is reflected from the free surface, it could be considered as part of the multiples. However the mirror is typically imaged as a "primary" with a mirror source (in a symmetric media above the free surface). In both the down and up-going cases, the multiples can extend the illumination of the primaries.

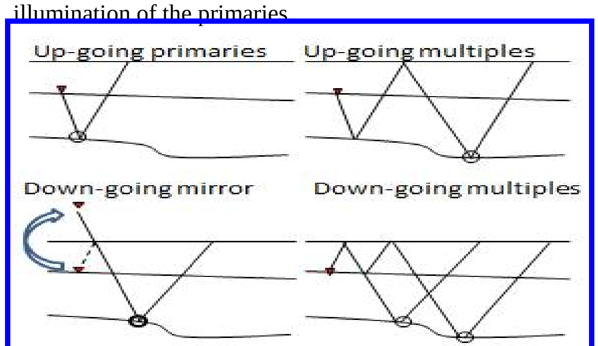

Figure 7 Raypaths for OBS imaging of up-going and down-going wavefields.

OBS acquisition is based on either ocean bottom nodes (OBN) or ocean bottom cables (OBC). Consider the example of imaging of OBC data acquired at Jubarte field in offshore Brazil (Lecerf, et al, 2015, Lu et al, 2015). The acquisition system used in this case was a fiber optics cable system with dense source shooting. An acquisition schematic is shown in Figure 8. Data for the up-going primaries, up-going multiples, down-going mirror, and down-going multiples were each imaged for this data. Shallow depth slice images for each case are shown in Figure 9. These images show the extension of the subsurface image achieved through the inclusion of multiples in the imaging process.

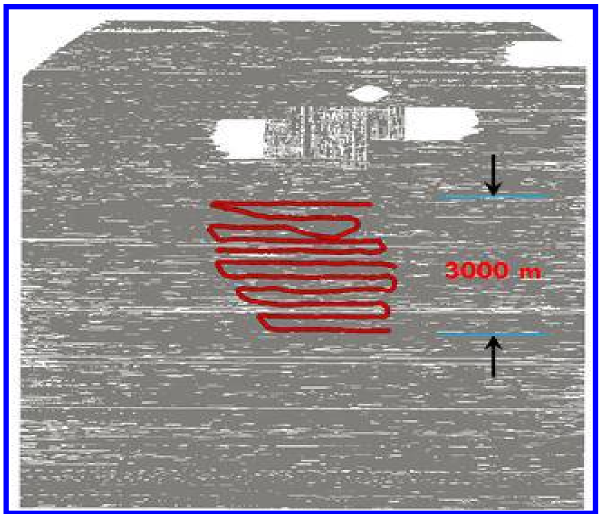

Figure 8. Shown is the configuration of OBS acquisition at Jubarte field - off shore Brazil. The cable layout is show in red and the dense shot distribution is shown in gray.

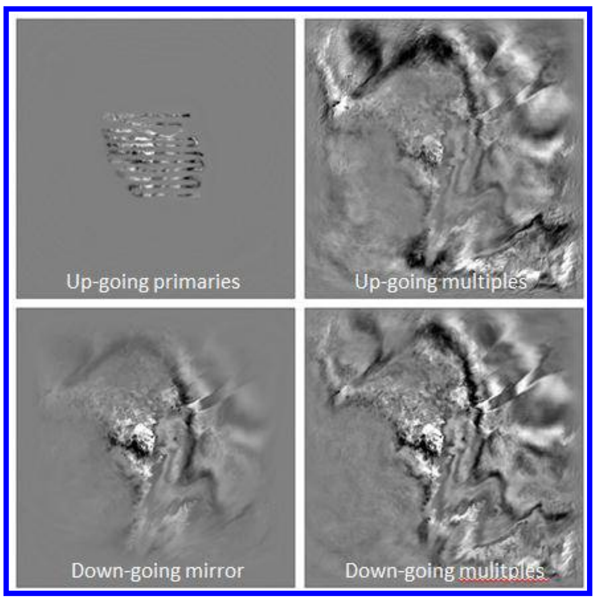

Figure 9 Shown are depth slices of images from up-going primaries, up-going multiples, down-going mirror, and down-going multiples. Note the signicant improvement in subsurface illumination from the mulitples and mirror reflections over the upgoing primaries.

Future state:

The most significant added value of multiples is occurs in acquisition configurations where both up-going and down-going wavefields are recorded. In areas of complex 3D structures or 3D stratigraphic detail, this requires some form of wide azimuth scenario. Critical acquisition design components in obtaining value from multiples are the spatial sampling and areal distribution of sources and receivers. There is tradeoff between the cost of increasing the sampling of sources (WAZ) or receivers (OBS) to improve the image from primaries compared to the added value from the complementary image from multiples. It is likely this will affect acquisition strategies in the future.

The imaging methods in this presentation focus largely on standard migration methods. However, the trend in imaging is some form of inversion. Also, there is more emphasis on including or mitigating internal multiples in the imaging process. An example of imaging the total wavefield, including primaries and free surface and internal multiples, is closed loop full wavefield migration (Berkhout, 2012, Davydenko and Verschuur, 2014, Berkhout, 2014). In this approach, a recursive extrapolation scheme is used to image the reflection response at each depth (from above and below). Both primaries and multiples are modeled by several "round trips" of the extrapolation process, and the reflectivity is iteratively updated by minimizing a cost function of the form:

$$J = \left\| P_{obs}(z0) - P_{\mathrm{mod}}(z0) \right\|_2^2 + f(R)$$

This approach along with least squares migration and full waveform inversion are becoming more prevalent. The challenge for all inversion methods is to effectively incorporate multiples in the inversion strategy, achieve high resolution images and ultimately include elastic effects.

Conclusions

In 3D wide acquisition the images from primaries can be complemented by images from multiples. In OBS and VSP wide azimuth acquisition mirror images can further improve the subsurface image. The major improvement in the use of multiples occur when there is a higher density of receivers relative to shots (as in WAZ surface seismic) or a higher density of shots relative to receivers (as in OBS).

In the future it is likely that imaging technologies move from migration to inversion based technologies. The prevalence of wide azimuth acquisition surveys (whether WAZ or OBS) will be controlled by economics. Certainly the potential of the value added from multiples will have some effect on acquisition strategies.

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EDITED REFERENCES

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