Challenges in Processing Variable-depth Streamer Data

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Summary

Variable-depth streamer acquisition is emerging as a key technique for providing wide bandwidth seismic data. With several data sets acquired across the world, it has consistently produced high quality images in terms of seismic resolution, layer stratigraphy and low-frequency penetration. By varying receiver depth, variable-depth streamer acquisition introduces receiver ghost diversity over different offsets. Such diversity enables a joint deconvolution method to fully remove the receiver ghost. Variable-depth streamer data also tends to be less noisy due to the deep tow of cables. These two factors allow variable-depth streamer data to have a spectrum from 2.5 Hz up to the source notch. Challenges in processing include: how to maintain the full bandwidth in the data, how to effectively remove multiples, and how to robustly build a velocity model. This paper will discuss each of these challenges and their solutions.

Introduction

Over the years, considerable efforts have been put into improving the bandwidth of marine seismic data. The core idea of these efforts is how to overcome the bandwidth limitation imposed by receiver ghost. For a conventional flat streamer, receiver ghost generates notches around the following frequencies:

\[ f = \frac{nv}{2d}, \quad n = 0, 1, 2, ... \]

where \( v \) is the water velocity and \( d \) is the receiver depth. The first not-zero frequency notch \((v/2d)\) has been the limit of usable seismic bandwidth. To increase resolution, one needed to move the cable shallower (smaller \( d \)). However, this may result in stronger swell noise and a deeper notch at zero Hz, and thus is detrimental to the low frequency signals. Such low frequency signals, in many geological settings like sub-salt plays in the Gulf of Mexico, are extremely important. A technique is needed that can widen the bandwidth at both ends of the spectrum.

Soubaras (2010) introduced a concept called “BroadSeis”, which allows receivers to have various depths along a streamer. Starting from the nearest channel, the receiver depth increases with offset, introducing diversity in receiver ghosts. This diversity enables us to fully remove the receiver ghost by using an advanced joint deconvolution algorithm (Soubaras 2010). The resultant seismic image has much wider bandwidth in both ends of the spectrum than that of conventional data. At the same time, acquiring such variable-depth streamer data is not more complex than conventional data because the main change is to tow the streamer at pre-defined variable depths.

To prove the concept, several variable-depth streamer data sets across the world have been acquired and properly processed. The obtained images are consistently better than conventional data in terms of vertical and lateral resolution, low frequency penetration, and layer stratigraphy.

To obtain such improved images, the standard marine processing flow has to be adjusted to accommodate the wide bandwidth of the data and to address the issues related to a variable receiver ghost, which is a direct result of variable receiver depths. The spectrum can extend from 2.5 Hz to 150Hz, which is much wider than that of conventional data. Therefore, one of the challenges is how to preserve this wide bandwidth during processing stages. Another challenge is how to deal with the variable receiver ghosts in the SRME step because the multiple model can have very different ghosts from the data. The third challenge is velocity analysis because a primary event and its ghost have different curvatures in CIG gathers. In the following sections, we will discuss these challenges and show some PSTM images to highlight the advantages of variable-depth streamer data.

Noise Contamination

By towing the streamer deeper (as deep as 60 meters), we expect the background noise level such as swell noise to be lower. This will allow us to recover more signals at low frequency (>2.5 Hz). Figure 1 shows typical shot gathers from conventional flat streamer and variable-depth streamer data. As expected, the noise level on the variable-depth streamer gather is much lower except for some near channels. This is indicated by their respective signal/noise (S/N) ratios. In these, the noise was averaged over all the channels above the water bottom, and the signal was measured right below the water bottom. Even with the high S/N ratio, the shot-domain de-noise can still be very challenging because of our desire to preserve as much low-frequency signal as possible. The typical 3Hz low-cut filter, for example, should not be applied to variable-depth streamer data.

Multiple Attenuation

Variable-depth streamer data present new challenges for de-multiple methods such as SRME and Radon. Here we highlight some of the issues with SRME.

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The main issue with SRME is how to handle the wavelet variation due to variable receiver depths from near to far offsets. By convolving the traces with different wavelets, the conventional SRME method (Berkhout and Verschuur 1997) produces multiple models that can have very different wavelets from the input data, and the difference varies from offset to offset. How to normalize the wavelet is the key to an effective application of SRME. This problem can be partially handled by adjusting the model wavelet in common offset domain. Figure 2 shows shot gathers before and after SRME for both conventional and variable-depth streamer data. Two observations can be made: first, the multiple on the variable-depth streamer data is not as obvious as that of conventional data; secondly, the de-multiple effect is about the same between the two data sets. However, more detailed examination of the results shows this conventional SRME is not optimal. A more sophisticated method has been developed (Sablon et al, 2011).

Velocity Analysis and Migration

Unlike conventional data, the receiver ghost in variable-depth streamer data can appear as a separate event from the primary event. They have different curvatures as shown in Figure 3. This thus leads to a lower resolution in velocity semblance and uncertainty in curvature picking. With the de-ghosting algorithm (Soubaras 2010), we are able to remove the ghosts before any velocity analysis. As shown in Figure 3, the semblance becomes sharper and allows more accurate velocity determination. For standard tomographic velocity update. This does mean that we have to de-ghost the gathers for each iteration of velocity model building.

Following velocity model building, migration is the next challenge. The wide frequency bandwidth puts high constraints on imaging. At the high frequency end, migration grid should be small enough to preserve high frequencies when the targets are high-dip events. In some cases, we have to use a bin size of 6.25 meters. At the low frequency end, migration algorithms have to be adjusted to deal with extra low frequency signals. The RTM boundary
condition, for example, needs special care so that artifacts will not be created during the migration.

Final PSTM Images

By overcoming these challenges, we managed to obtain images that are superior to conventional images in terms of vertical and lateral resolution, low frequency penetration, and layer stragigraphy. Here we use three examples to illustrate the point.

The first example is from offshore West Australia (Figure 4). The broad bandwidth (Figure 5) of variable-depth streamer data is well displayed in the image. Compared to conventional data, the extra low frequency energy gives the layers different textures that may be related to rock properties. In addition, the high frequencies crisply delineate the layer boundaries. Another important observation is that the brightness (light or dark) of the layers conforms to the layer structures. This indicates a good phase control in the low frequency.

The second example is from the Gulf of Mexico (GOM). The cable was lowered gradually from near channels to far channels. This configuration allowed us to obtain a spectrum from 2.5 Hz to 166 Hz. The 2D time migration image is shown in Figure 6. The high frequency is evident in the shallow part. But more importantly, the low frequency signal below the salt is much stronger than that in the conventional image. This enhanced signal will help image base of salt and sub-salt structures. We expect variable-depth streamer data, together with wide azimuth acquisition, will play an important role in subsalt exploration in GOM.

The third example is from the central North Sea. This is a 3D survey with a shallow ocean bottom (about 100 meters). The most challenging task in processing this data set was how to attenuate the multiples without damaging both primaries and receiver ghosts. Tests show Shallow Water De-multiple (SWD, Hung et. al, 2010) plus Taup-Decon is the most effective sequence. Details will be presented in Sablon et al (2011). Figure 7 shows the time slices from the final conventional and variable-depth streamer images. The broad-band nature of the data is also well displayed on the time slices. Numerous fine structures are present in the background of black, white and red colors, which may indicate the different rock properties. By comparison, the conventional image lacks such richness and appears noisier.

Conclusions

Data examples show that use of a variable-depth streamer can provide a very wide spectrum. It is superior to conventional data in terms of seismic resolution and low frequency penetration. A good processing flow should be able to preserve high- and low-frequency signals, and carry them into the final images. Key challenges are in the steps of noise and multiple attenuation, velocity analysis and migration.

Acknowledgements

We thank CGGVeritas for permission to publish this paper. We also thank Salvador Rodriguez & Robert Dowle for promoting variable-depth streamer test campaigns, and Richard Wombell and Terje Weisser for their help with the Central North Sea data.

Figure 4. PSTM images from offshore West Australia. The conventional image is on the left, and the image from variable-depth streamer data is on the right. Amplitude spectra are shown in Figure 5.
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Figure 5. Amplitude spectra for conventional data (blue) and variable streamer data. The corresponding seismic sections are shown in Figure 4.

Figure 6. PSTM images from the Gulf of Mexico: conventional data on the left and variable-depth streamer data on the right.

Figure 7. Time slices from 3D surveys in Central North Sea: conventional data (the top panel) and variable-depth streamer data (the bottom panel)
EDITED REFERENCES
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