The Impact of the Receiver-side Ghost on 4D Monitoring Using Broadband Seismic

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SUMMARY

Increasing the seismic resolution by extending the signal bandwidth has been a technology driver for the seismic industry over recent years. Although some remarkable marine exploration case studies have validated the concept of 3D broadband images, the technology has not shown its full potential in a 4D context. In this paper, we will describe advantages of data acquired using a dual-sensor towed streamer for 4D seismic applications.

Introduction

Increasing the seismic resolution by extending the signal bandwidth has been a technology driver for the seismic industry over recent years. Today, the seismic industry is proposing new resolution standards for 3D imaging using seismic data with an extended bandwidth using either specific acquisition technologies or processing techniques attempting to recover bandwidth from conventional new or legacy surveys. One of the key challenges in this regard is correcting for the sea-state and its impact on ghost reflections. The success of this can be critical in providing the required increase in bandwidth. This subject has been discussed by several authors, with an interesting summary provided more recently by Grion et al., (2013).

In a 4D setting acquisition repeatability may prove even more challenging for some broadband acquisition systems where the precise cable depth and sea-state characteristics play an important role in providing the receiver de-ghosted data (Williams and Pollatos, 2012). This problem does not exist when data are acquired using a dual-sensor towed streamer (such as *GeoStreamer*®) comprising pressure and vertical particle velocity measurements. The characteristics of the sea-surface are inherently mimicked on the total pressure and velocity recordings allowing the receiver ghost to be removed in an accurate and robust manner, generating separated up-going and down-going wavefields.

Since the receiver ghost is affected by the sea-state, the down-going wavefield is a source of *non-repeatability,* increasing with frequency. Measurements used for 4D studies strive to maximise *repeatability* so it is important to ensure that the less repeatable part of the signal is removed. Using the up-going pressure field for base and monitor acquisitions represents the ultimate solution for high resolution 4D seismic, opening the door to more precise and reliable time-lapse measurements.

4D broadband seismic from a dual-sensor towed streamer

A time-lapse project involves repeating 3D seismic surveys over a producing reservoir. But why have broadband technologies not yet been fully adopted for 4D monitoring? For this to transpire the following requirements need to be fulfilled:

- The benefits of broadband data for 4D reservoir characterization must be conclusively demonstrated (in 3D this is already well understood and illustrated, e.g. Reiser, 2012).
- 4D broadband seismic has to be seamlessly integrated into existing 4D cycle processes which currently utilise conventional seismic vintage datasets.
- Risk assessments / feasibility studies have to be performed justifying 4D broadband acquisition for new challenging reservoirs.

Dual-sensor towed streamer data has successfully addressed the two first requirements due to its ability to perform both wavefield separation, providing the up-going and down-going pressure wavefields, and wavefield extrapolation to new cable depths (Söllner et al., 2008). This capability allows new broadband monitor surveys to be matched with legacy narrow bandwidth vintage data (conventional hydrophone-only streamer data) acquired at different cable depths (e.g. Day et al., 2010). This ensures full backward compatibility for continuing the 4D reservoir monitoring cycle, in addition to providing opportunities for high-resolution broadband time-lapse surveys in the future.

Extending the frequency bandwidth of 4D data will increase the sensitivity of the seismic response to reservoir changes and may in fact make the repeatability even more challenging. However, using the additional high-frequency information should ultimately improve the detectability of velocity variations due to hydrocarbon production at the reservoir level; the challenging part will be the control and removal of the 4D noise created by small travel-time variations due to acquisition and environment variability.

The receiver ghost is not 4D friendly

Varying sea-state conditions have been recognized as a significant challenge for time-lapse studies due to the impact of the sea-surface on the ghost reflection, e.g. Laws and Kragh (2002); the impact on seismic data can be well illustrated using a dual-sensor towed-streamer. The cable is typically towed significantly deeper than during conventional acquisition so the different behavior of the up-going and the down-going pressure fields is more easily observed on the raw data. This is illustrated in figure 1 where the early reflections in a common shot point gather are shown for the particle velocity sensor, the pressure sensor and the reconstructed up-going pressure wavefield respectively.

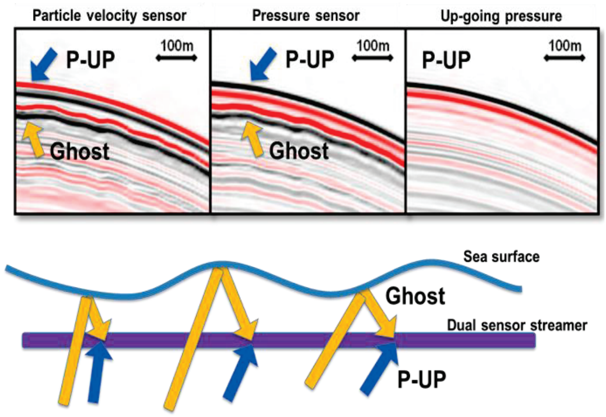

Figure 1 *Zoom on a common shot gather showing the recording of the vertical particle-velocity sensor (left), pressure sensor (middle) and the reconstructed up-going pressure wavefield (right). The receiver ghost undulation (yellow arrow) is due to the sea surface reflection while the up-going pressure wavefield (blue arrow) stays continuous. The data shown were acquired in Brazil with a 20m cable tow depth with sea conditions reported as 4 meters of swell.*

(Image adapted from Burren et al., 2013.)

We clearly observe the receiver ghost kinematic, present on the first two panels, is affected by the undulation of the sea surface (swell). Figure 1 demonstrates the importance of removing the receiver ghost reflection over the full signal bandwidth in order to minimize the 4D noise. The right panel shows the up-going pressure wavefield which is not affected by the sea state and therefore represents the desired platform for broadband 4D experiments. This example was acquired in Brazil and is typical of data from the deep water basins where surveys are exposed to variable and often considerable South Atlantic swell conditions. However, the same characteristics will exist in other parts of the world where sea conditions are anything other than flat-calm.

The ability of a dual-sensor system to perform accurate wavefield separation provides an opportunity to extrapolate the up-going and down-going wavefields to alternative cable depths. By summing the redatumed wavefields, a new total pressure wavefield is created equivalent to a conventional hydrophone-only streamer dataset; this “backward compatibility” of dual-sensor data provides a feasible and demonstrated option for reservoir monitoring using a combination of dual-sensor and conventional streamer data (Day et al., 2010). Just as with conventional streamer data, such a 4D study would be exposed to variations in the sea-state between the different vintages of data.

An alternative approach, available when one of the datasets has been acquired using a dual-sensor streamer, is to recreate the total pressure wavefield with a “perfect” receiver ghost by making simple assumptions about the sea-state to impose a controlled ghost function onto the up-going pressure wavefield. This is illustrated by figure 2: in the left panel, the redatumed up-going and down-going pressure fields have been combined to re-create the total pressure field at a 7m cable depth (this record will inherently include all the sea-state effects observed in the field); the middle panel shows the up-going wavefield with a modeled receiver ghost function imposed, representing significantly calmer sea conditions than experienced in the field; the difference between the first two is shown in the right panel providing an example of the non-repeatability of the down-going wavefield.

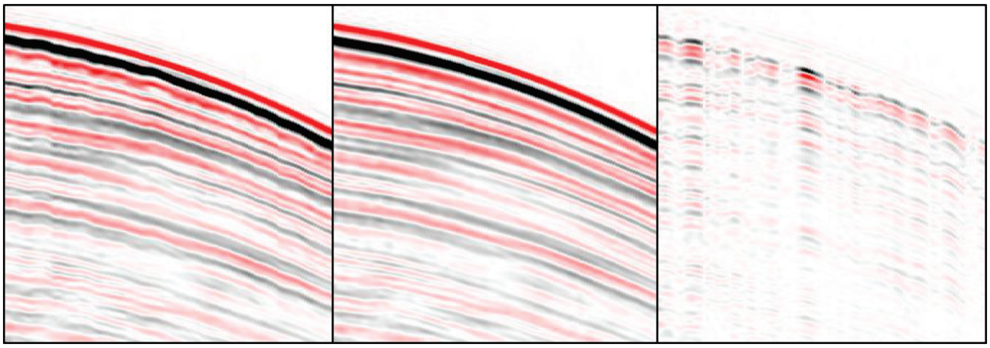

Figure 2 *Shot records illustrating different receiver ghost effects. The left panel shows the recreated total pressure field at 7m, the middle panel shows the same data recreated using a modeled receiver ghost (assuming a much calmer sea-state). The right panel is the difference. (The modelled ghost function assumed a sea-surface reflection coefficient of -0.99 and a cable depth of 7m±0.5m.)*

These variations in receiver ghost caused by marginal sea-states may provide some benefits when using processing based solutions to de-ghost conventional streamer data for 3D imaging (Williams and Pollatos, 2012) but in a 4D setting the non-repeatable nature of the receiver ghost is likely to result in increased levels of 4D noise.

The benefits of using only the up-going pressure field for broadband 4D have been demonstrated using a multi-azimuth survey (MAZ) where two azimuths were acquired with dual-sensor towed streamer and a third azimuth was acquired with a conventional streamer design (legacy data). Figure 3 shows common image gathers for the same surface bin location extracted from the three different azimuths of the MAZ survey.

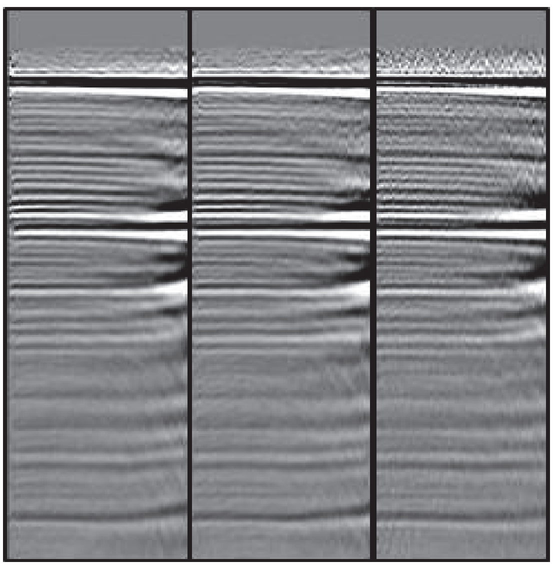

Figure 3 *Example of repeatability achieved with two up-going pressure wavefield gathers acquired using a dual-sensor towed streamer (left and center) compared to a conventional streamer data after application of processing-based de-ghosting (right). All three gathers show some complimentary characteristics, but the conventional streamer data is clearly much noisier due to the assumptions made during de-ghosting.*

In order to match the bandwidth of the two up-going pressure wavefield datasets, a pre-migration de-ghosting operator (which does not take into account the sea state) has been applied to the conventional data (Burren et al., 2013). The two up-going pressure wavefield gathers (left and center) show a superior resolution and signal-to-noise ratio as well as excellent repeatability despite being recorded at different azimuths. The conventionally acquired gather (right) is contaminated by high frequency noise due to the inability of the de-ghosting operator to correctly handle the variable sea-state. Figure 3 indicates that in the context of 4D broadband handling the variability of the high frequency information will be most challenging. The inability to accurately correct for sea-state variations in the de-ghosting process will create high frequency noise reducing the resolution of the 4D signal.

Conclusion

We demonstrate that dual-sensor towed streamer data provides a superior platform for broadband 4D surveys by combining pressure and particle velocity sensor information to provide the up-going pressure wavefield, free from the effects of receiver-side ghost. This process not only recovers the frequencies in the receiver ghost notches but also preserves the most repeatable part of the seismic signal by removing the sea-state effects on the receiver side. The down-going field (receiver ghost) is modified by the sea-state variations and is consequently not well suited for 4D broadband.

We propose that up-going pressure wavefield estimates are used for base and monitor surveys to ensure the best possible broadband repeatability and highest 4D resolution.

Acknowledgments

Thanks to PGS for permission to publish this paper and to use data examples from the PGS Multi-Client data library, and to the imaging teams in the Rio de Janeiro office for processing the data.

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