SUMMARY

One of the limiting factors in seismic resolution for marine towed-streamer acquisition is the ghost effect due to sources and receivers. The ghost is the reflection from the sea surface that interferes constructively or destructively with the primary reflections reducing the seismic bandwidth at the low end and the high end of the spectrum. Different acquisition and processing solutions were proposed during the years to address the ghost problem. In this paper we review these solutions and we introduce new slant streamer-type acquisition with the processing based on prestack single-streamer deghosting.
Introduction

One of the limiting factors in seismic resolution for marine towed-streamer acquisition is the ghost effect. The ghost is the reflection from the sea surface that interferes constructively or destructively with the primary reflections reducing the seismic bandwidth at the low and high ends of the spectrum. Acquisition and processing solutions to address the receiver ghost problem were introduced in early 1980s and again in the last five years; these are:

- Slant streamer (Ray, 1982)
- Over/under streamers (Sonneland, et al.1986)
- Hydrophone-vertical geophone streamers (Carlson, et al. 2007)
- Multicomponent (4C) towed- streamers (Robertsson, et al. 2008)

Slant streamer acquisition had very limited applications due to inadequate processing algorithms at the 1980s, particularly deghosting, or ghost-removal process. Over/under acquisition also had limited applications during that period due to deficiencies in marine acquisition technology related to lack of streamer control in vertical and horizontal planes, and reduced accuracy in receiver positioning along streamers. A more efficient 3D over/under marine acquisition method was introduced by Kragh et al. (2010). Recently, processing slant streamer data was revisited and new solutions were proposed. Soubaras (2010) introduced a deghosting method by joint deconvolution of migration and mirror migration of the data. In this paper we introduce new slant streamer-type acquisition with the processing based on prestack single-streamer deghosting.

Resolution of seismic data is also affected by the source ghost. Based on seismic reciprocity, a similar over/under solution that is used to remove the receiver ghost can be employed to remove the source ghost (Moldoveanu, 2000; Parkes and Hegna, 2011). In this paper we will discuss only the techniques that are used to address the receiver ghost.

Slant streamers

Slant streamer marine acquisition was proposed by C. Ray (1982) as a “high resolution, marine seismic stratigraphic system”. The novel idea of the slant streamer method was to have variable receiver depths along streamers and, inherently, variable ghosts from receiver to receiver, and to take advantage of this in the stacking process. The proposed processing method was to generate a stack section corresponding to the primary reflections after the primaries were aligned, and a stack section corresponding to the ghost reflections after these were phase-reversed, aligned, and stacked. The two stacks were combined. This approach was adequate for CMP stack-based processing. However, for a processing sequence that requires a consistent wavelet, such as multiple attenuation and velocity analysis, the proposed technique was not suited.

Post-migration slant streamer deghosting

Soubaras (2010) introduced a processing method for slant streamer data that requires performing migration of seismic data to generate the dataset $d_1(t)$, and mirror migration of seismic data to generate the dataset $d_2(t)$. Regular migration enhances the primary reflections and the seismic wavelet associated with the data has minimum phase. Mirror migration enhances the ghost reflections and the seismic wavelet left in the data is maximum phase. The deghosting process is implemented post-migration, in time domain, as a minimum-maximum phase joint deconvolution of $d_1(t)$ and $d_2(t)$ to obtain an estimate of reflectivity. As the seismic wavelet is variable due to the ghost change from receiver to receiver, the method requires adjusting the variable seismic wavelet to perform surface-related multiple attenuation and velocity model building (Dechun et al. 2011). Examples of slant streamer data processed with these techniques were presented in Dechun’s paper and in Soubaras’ 2010 paper.

Prestack slant streamer deghosting

The method we propose for processing slant streamer data is to perform receiver deghosting at the early stage in seismic data processing to take advantage of the 3.125-m point-receiver sampling inherent in the latest generation of streamers. The algorithm for single-streamer deghosting belongs to
a class of algorithms known as spectral reconstruction (Ozdemir et al. 2008). In frequency wavenumber domain this algorithm can be formalized as an inversion problem:
\[ [Data] = [G][U] + Noise, \]
where: \( Data \) is the vector representing the spectral component of input data; \( G \) is the matrix representing the ghost operators, and these depend on receiver depth, sea surface reflection coefficient and water velocity; \( U \) is the unknown spectral component of the upgoing wavefield or deghosted pressure; and \( N \) is the noise vector which is part of the input data not explained by the ghost model.

A feasibility field test was conducted with slant streamer configuration during a multivessel coil acquisition program in the Gulf of Mexico. A typical acquisition configuration for multivessel Coil Shooting consists in two streamer vessels and two source vessels (Moldoveanu and Kapoor, 2009). Each streamer vessel has 10 streamers, 8 km in length and 120- m streamer separation. Cables are deployed at 12 m depth. A single source array is deployed at 10 m of depth on each vessel. One coil was repeated with the streamers deployed in a slant mode, the variable receiver depths being from 12 m to 32 m. The main objectives of this test were to determine if coil acquisition can be performed in a slant mode and also to determine how the seismic bandwidth can be expanded by using the new proposed processing for slant streamer acquisition. As the main objectives of multivessel coil surveys in the Gulf of Mexico are deep subsalt reservoirs, we were interested in enhancement of the low frequencies and preservation of the maximum frequencies up to 70 Hz. The preliminary processing sequence applied on flat and slant coil data is described in Table 1.

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<thead>
<tr>
<th>Coefficient coefficient</th>
<th>Coefficient coefficient</th>
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<tr>
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<td>Raw sensor measurement (3.125 m inline sampling)</td>
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<td>Noise attenuation</td>
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<td>Source designature (source and receiver ghost in the desired signature)</td>
<td>Source designature (source ghost in the desired signature)</td>
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<td>3D Kirchhoff depth migration to 70-Hz maximum frequency</td>
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<td>3D RTM depth migration to 30-Hz maximum frequency</td>
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Table-1 Processing sequence applied on coil shooting horizontal streamer and slant streamer data

At the time this abstract was written 3D demultiple was not applied, but it will be part of the final processing. Kirchhoff prestack depth migration results for coil acquisition horizontal streamer and slant streamer data are presented in Figure-1 and Figure-2, respectively. These results prove that slant streamer acquisition and proposed processing enhance the low frequencies and preserve the medium and high frequencies.

Over/under streamers

Practical 2D applications of the over/under method started in 1984 in the North Sea (Sonneland et al.1986). The method was introduced as a means to reduce the weather downtime by deploying two streamers on top of each other at large depths, such as 18 m and 25 m, to minimize the effect of swell noise. Seismic wavefield recorded by the over streamer at depth \( d1 \) and the under streamer at depth \( d2 \) can be written as a sum of upgoing \( U \) and downgoing \( D \) wavefields:

\[ S1 = D1 + U1, \quad S2 = U2 + D2 \]

Several methods have been proposed to separate the upgoing wavefield –e.g., Sonneland et al. (1986), Ozdemir et al. (2008). The limitations of towed-streamer acquisition technologies during 1980s prevented the use of this method at that time. However, with the introduction of new marine acquisition technology that has accurate positioning and advanced streamer control, the over/under
method has been used in the last 6 years, mainly for 2D applications (Bunting 2011). The use of the over-under method for 3D applications is currently limited (Moldoveanu et al. 2007), as it requires pairs of streamers, and this reduces the conventional acquisition footprint by half.

Kragh’s method is a modification of over/under acquisition that relaxes the requirement for deeper streamers, used for low frequencies, and keeps the same number for shallower streamers, to optimize middle and higher frequencies. The combination of deep and shallow datasets provides full offset broadband seismic data with good signal-to-noise ratio at the low and high ends of the spectrum.

Recent applications of over/under acquisition for 2D seismic exploration in offshore India sub-basalt areas, and sparse-under acquisition for 3D exploration programs offshore Australia, India, and South Africa, demonstrated the value of these acquisition and processing technologies for improving seismic resolution and low-frequency content of the seismic data, in addition to resilience to marginal weather conditions.

**Hydrophone-vertical geophone (dual sensor) streamers**

A marine seismic system that measures the seismic pressure wavefield using hydrophones, and the vertical component of particle velocity using motion sensors was proposed by Berni (1982). However, in 2007 a dual-component marine streamer was introduced that measures pressure with hydrophones and, simultaneously, the vertical component of particle velocity, with gimbal-mounted vertical geophones (Carlson et al. 2007). One advantage of this system is that the two independent measurements can be combined to perform separation of upgoing and downgoing components of the pressure wavefield for all offsets. Theoretically, broadband temporal seismic data can be acquired due to elimination of the receiver ghosts and improved low frequencies by deploying the streamers deeper (Semb et al. 2010). Such a system allows us also to reduce the weather noise and to increase the acquisition efficiency by extending the weather acquisition window.

**Multicomponent (4C) towed streamers**

The concept of multicomponent towed streamers was introduced by Robertsson et al. (2008). The system measures pressure with hydrophones, and particle acceleration in x, y and z directions with micro electromechanically systems (MEMS) three-component accelerometers. As from acceleration the gradient of the pressure can be derived, the multicomponent streamers provide measurements of pressure and gradient of pressure in three directions. Based on these measurements wavefield separation of upgoing and downgoing components can be performed, and, in addition, crossline wavefield reconstruction (Ozbek et al. 2010). The multicomponent (4C) system enables us to calculate the 3D upgoing wavefield at any desired position within the spread, for instance a densely sampled grid of 6.25 m x 6.25 m, and this allows improving not only the temporal bandwidth, but also the spatial bandwidth. Multicomponent streamers can be deployed at larger depths and this improves low-frequencies content, signal-to-noise ratio due to reduced swell noise, and acquisition efficiency. Operational efficiency can be further improved by using multicomponent towed-streamer data to detect and eliminate seismic interferences (Vassallo et al., 2012).

**Discussions and conclusions**

Ghost removal is an important part of improving the frequency bandwidth, and different acquisition and processing techniques are available. A deghosting solution for slant streamer relies on ghost notch variability from receiver to receiver. Over/under and dual-sensor streamers collect pressure and additional measurements that are used to deghost the data for all offsets. The advantage of multicomponent streamers vs. the other methods comes from pressure gradient measurements in x, y, and z directions, which allows reconstruction of seismic data in the crossline direction, achieving a double impact on seismic resolution.
Introduction of these methods in standard practice opens the possibility to tackle more effectively the challenges we face in difficult geologic areas that require higher seismic resolution, temporally and spatially, and improved signal-to-noise ratio.

Figure 1 Kirchhoff depth migration image of horizontal streamer coil shooting data

Figure 2 Kirchhoff depth migration image of slant streamer coil shooting data

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