Sparse seabed seismic acquisition for 3D/4D reservoir imaging using high-order multiples. Application to Jubarte PRM.

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Abstract

A receiver decimation study has been performed to assess the potential of using sparse receiver grids in conjunction with high-order multiples imaging techniques for 4D reservoir monitoring. Reducing the density of receivers in a PRM (Permanent Reservoir Monitoring) will reduce the capital expenditure for system installation. For OBN (Ocean Bottom Node) acquisition, cost savings can be achieved from more effective node deployment. The seismic imaging process makes use of the multiple sea-surface reflections to significantly increase the subsurface fold of coverage, hence compensating for the reduced number of sensors. We will show that with the above imaging technology it is possible to use a sparser seabed recording geometry without compromising the 3D or 4D image quality. Using the Jubarte PRM dataset acquired by Petrobras, the decimation test consists of selecting all receivers in consecutive sub-sections of 600m length along the cable, effectively splitting the receivers into circular patches with a 600m diameter. The number of sensors is then reduced by a factor two. The results demonstrate that by using state-of-the-art imaging methods it is possible to increase the sparseness seabed sensor locations without compromising the resolution of 3D/4D imaging.

Introduction

Seismic seabed acquisition, whether OBC (Ocean Bottom Cable) or OBN (Ocean Bottom Node), benefits imaging offshore reservoirs when full azimuthal illumination is needed or when field infrastructure obstructs surface acquisition. Such acquisition can offer wide azimuth and long offset illumination with a little operational constraint for the acoustic source part because the shooting vessel is not physically connected to the recording system. However, the receiver deployment on the seafloor may require more complex operations, especially in a deep water environment. In addition, seabed infrastructure installations (flow line, well head, pumps, anchors, etc.) may challenge the receiver layout geometry and add extra cost.

The economic benefit of reducing the number of receivers is obvious but a critical number of sensors are necessary in order to assure a minimum fold of coverage. Receiver spacing requirements for seabed acquisition have been extensively commented on the literature. Most of the OBC case studies, using the standard up-going wavefield imaging, have a maximum receiver line separation in the region of 300 m and 100 m distance between sensors along the cable. Beyond these limits, the image may suffer from lack of continuity and resolution. In a deep water environment, the use of the down-going wavefield, with mirror imaging, allows the recording disposition to be stretched. For example, an OBC grid of 100 x 400 m is used for an optimum compromise on the Aganota-BC-10 field with water depths of 1600-1700 m (Galagara & al., 2015). In another deep water OBN example, a receiver spacing using a grid of 450 x 450 m has been recommended for preserving the imaging resolution (Olofsson & al., 2012). Reviewing numerous cases, 500 m receiver separation seems to be an established maximum for preserving a decent signal-to-noise in the final seismic image.

For our study, we used the deep water Jubarte PRM pilot dataset acquired by Petrobras with an initial receiver grid of 50 m x 300 m. Permanent reservoir monitoring (PRM) installations can be considered as the best solution for detecting small seismic signal variations related to reservoir production. We simulate the impact of a sparse geometry by creating receiver gaps, larger than 500 m, within the survey layout.

PRM Jubarte: Deep water context

In 2012, Petrobras installed the first deep-water optical PRM system provided by PGS in the Campos basin (Figure 1a). This pilot project covers ~10 km2 with the primary objective being to validate the fiber optic sensing technology's capability to detect subtle impedance changes in the Jubarte reservoir. The layout of the 35 km optical cable was designed for the up-going seismic wavefield imaging. The main challenge was to optimize the cable layout and the density of multi-component receivers for ensuring an effective 4D seismic detectability whilst avoiding any crossings of the existing subsea infrastructure, (Thedy et al., 2013). 712 four component optical sensors were deployed in water depths varying from 1250 to 1350 m. The receivers are positioned every 50 m along the cable and the layout simulates 11 receiver-lines separated by ~300 m (Figure 1b). The source grid covers an area of 11 km x 11 km with 25 x 25 m shot spacing.

The first 4D signals were observed after one year of reservoir production using the active seismic surveys completed respectively in early 2013 and early 2014. The resulting monitoring image has been limited to the area of ~10 km2, which proved sufficient for validating the deepwater pilot installation. The quality of the 4D seismic signal demonstrates the high detectability expected from a permanent optical installation.

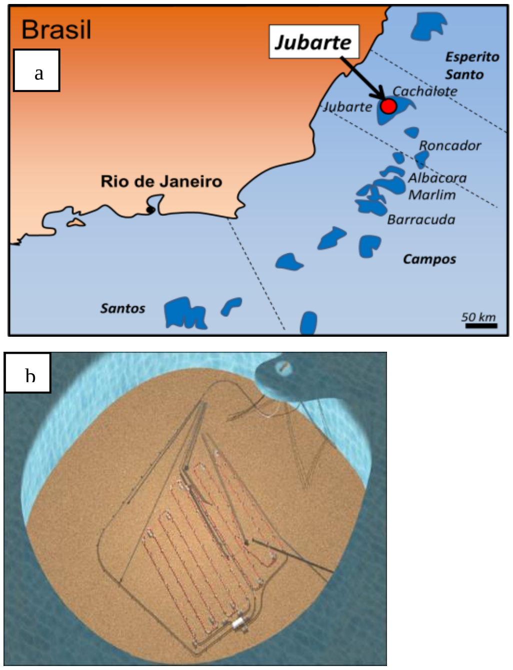

Figure 1*: a) Jubarte field location, north campos bassin. b) Layout of the 712 seabed optical sensors (in red)*

High-order multiples imaging for seabed acquisition

The 4D Jubarte datasets were used for validating an original 3D/4D imaging solution that uses all the recorded seismic wavefields, primary reflections and sea-surface multiples (Lecerf & al., 2015). To summarize the imaging concept, the source wavefield composed from all recorded data is forward extrapolated, the receiver wavefield composed from the same recorded data is backward extrapolated and an image is constructed by applying a deconvolution imaging condition of the two wavefields (Lu et al., 2015). The 4D image is then computed with the image difference of the base and monitors.

For OBC/OBN acquisition using conventional imaging technique, the illumination map can be estimated directly from the shot and receiver location (figure 2a, P-UP: blue line). Nevertheless imaging with multiples uses every order of sea-surface reflections available in the data. The illumination, retrieved from a single source-receiver pair, contains numerous hit points at the target level. In fact, the methodology transforms every shot pair into a virtual sea-surface source-receiver system (figure 2a). The illuminated area is essentially defined by the surface distribution of the seismic sources and the maximum order of multiples recorded.

Figures 2b and 2c show the comparison between an image provided by conventional up-going primary reflections and an image computed from all orders of multiple available in the records. It can be noticed that the up-going image is limited by the 3km extent of the receiver array while the image using all sea-surface reflected wavefields is defined by the source distribution covering 10 km.

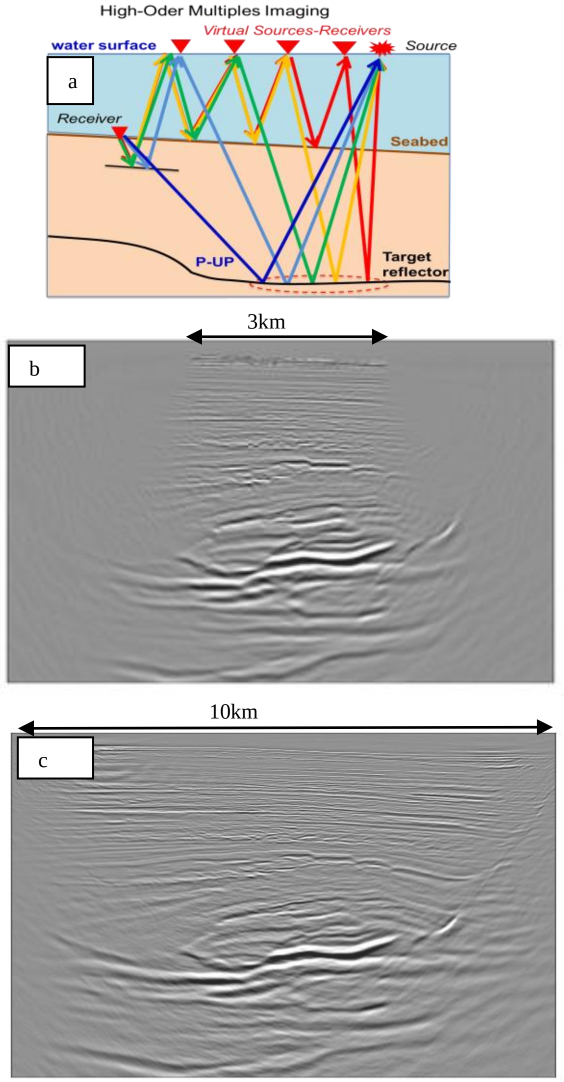

Figure 2*: a) Target illumination schemes for a single source-receiver pair. b) 3D image section computed from up-going primary reflections only (P-UP). c) 3D image section computed from all order of multiples.*

Receiver Decimation Test

The illumination surface enlargement is not the only benefit of using sea-surface reflected wavefields (i.e. high-order multiples). Because of the multiplicity of the sea-surface reflections, the density of “hit point” at the target is significantly increased. Due to the improved illumination, proportional to the number of orders of multiple present in the record length, we should be able to increase the sparsity of the receivers without much impact on the image resolution. The shot distribution and the quality of the multiple records become more crucial for the illumination than the layout geometry of the seabed sensors.

One of the decimation scenarios was to mimic a very sparse acquisition with “receiver holes” of 600 m diameter. Creating such holes in the initial receiver layout halves the effective number of receivers. Figure 3f describes the sensor geometries selected for the decimation tests. Two subsets of 350 receivers were created with 34 sections of ~10 'continuous receivers' (with the initial 50 m separation) along the cable. Sections, for each subset, are then separated by around 600 m in both directions. The same shots were processed for the two decimation sets. Figure 3a and 3b show respectively the 3D seismic image section and the 4D image difference created with the full set of receivers (Set1+Set2: ~700 rec) used as the reference for the decimation test.

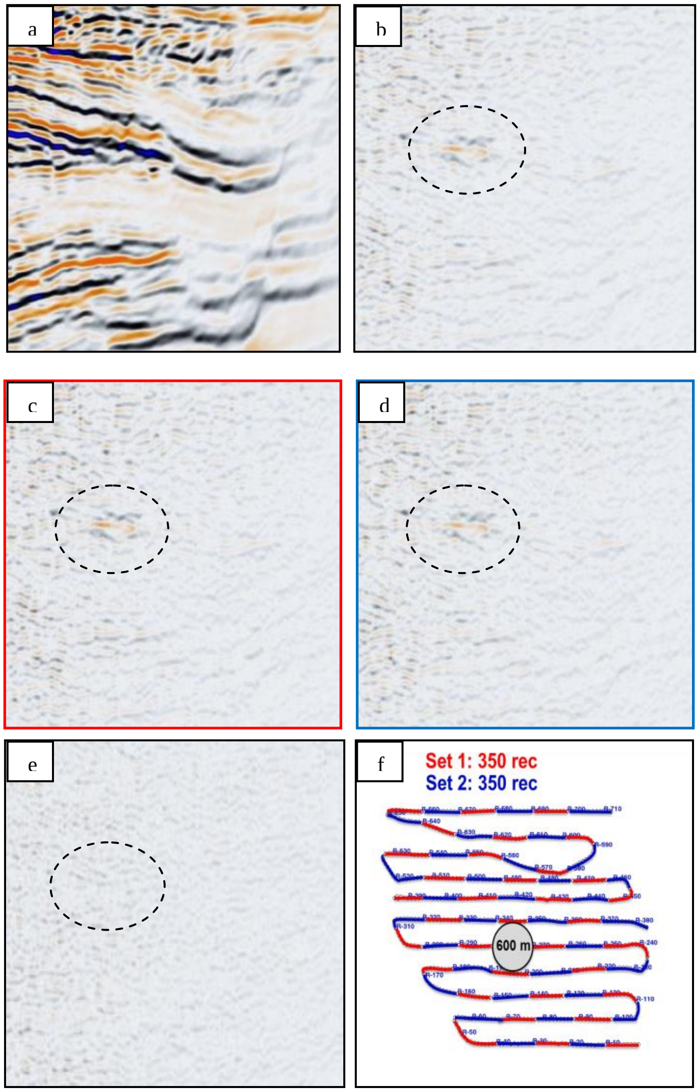

Figure 3:

a) Reference 3D image section, full set 700 receivers.

b) Reference 4D image difference, full set 700 receivers.

c) 4D difference subset 1 350 receivers.

d) 4D difference subset 2 350 receivers.

e) Difference of the two 4D differences (4D subset1- 4D subset2)

f) Scheme of the receiver decimation. Two subsets (blue and red) of 350 receivers are composed from 34 sections of ~10 receivers (with 50m separation). For each subset, the gap between sections corresponds to a circle of 600m diameter.

The 4D signal, visible in the central part (figure 3b), has been extracted by calculating the difference between two "high order multiples" images from two surveys acquired a year apart. This is a "raw" 4D difference as no specific 4D cross-equalization, de-noise or post-processing has been applied. Some 4D noise appearing in the background can be observed. This noise seems to come from the water velocity variation affecting the source repeatability between the surveys, and can be attenuated pre or post migration using cross-equalization filters. The "raw" 4D seismic is used as reference and we will focus on the 4D full stack image resolution associated to the receiver's decimation.

Figures 3 c) and 3 d) show respectively the 4D differences computed using the subset1 and the subset2 geometries. No difference in term of 4D resolution can be observed between these 4D images using the decimated sets and the one using the full set (figure 3b). The 4D signal is remarkably preserved despite the large gaps in receiver coverage in the layout. Interestingly, the 4D noise is repeated as well for the three cases. It can be attributed to the non-repeatability on the source side, as the three 4D images share the same shots. Remarkably, the ratio 4D signal/noise is similar for each case.

For both decimation cases, the base and monitor surveys use the same set of 350 receivers, which assures optimum repeatability. Imaging using several orders of multiple makes use of the intrinsic redundancy of reflection information which infill the illumination hit count over the 600 meter patches without sensors. Furthermore, the similarity and consistency between the 4D images provided by the two complementary sensor subsets demonstrates the disconnection between the seabed system geometry and the illumination. With the new imaging process, the resulting illumination is principally driven by the shot carpet (which is similar for base and monitor surveys).

Figure 3 e) shows the difference of the two 4D differences computed from the two decimated sets. The presence of only random noise indicates that either the 4D signal or the consistent 4D noise is insensitive to the seabed acquisition geometry. It confirms as well the excellent repeatability that can be achieved on the receiver-side using permanent optical cable.

Discussion

This decimation test demonstrates the potential of the "all sea-surface reflected wavefields imaging" to enable sparse seabed acquisition. However, the concept of acquisition sparsity should be clarified. This test shows that large gaps without sensor can be handled but a minimum of reflection redundancy has to be respected to assure sufficient image resolution. This means that the number of receivers is still essential for optimizing the signal-to-noise ratio in the final image stack process and the receiver reduction factor should not be excessive, but their location on the seabed is less important. Irregular receiver grid can be used for maintaining enough redundancy in an expanded area. This could have a significant economic impact on the OBC or OBN survey design and deployment as a larger area can be covered with stretched layout geometry and a reduced number of sensors. Also seabed infrastructures can be avoided without compromising the final image illumination.

Conclusions

A receiver decimation study has been performed, using the PRM Jubarte dataset acquired by Petrobras, for assessing the potential of really sparse seabed acquisitions in conjunction with high-order multiple imaging techniques. We have demonstrated that the imaging technique is appropriate for seabed datasets in both the 3D and 4D contexts. It makes use of the multiple reflections to significantly increase the illumination, therefore enabling sparser seabed recording geometry with receiver gaps larger than 500 m. The number of sensors is thereby reduced by a factor two. The results demonstrate that it may be possible to extend some commonly accepted spatial limits in terms of seabed sensor sparseness without compromising the resolution of 3D/4D imaging. For future seabed acquisition, the use of this new imaging technique provides more flexibility in the design of the receiver layout in addition to the economic benefits. Sensors can be placed further away from seabed noise generators (pumps, flow lines ...) in quieter zones on the seabed thereby improving the detectability of weak 4D signals without compromising the target illumination.

Acknowledgments

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