Very Sparse Seabed Seismic Acquisition for 3D/4D Reservoir Imagng with High-order Multiples. Application to Jubarte PRM

D. Lecerf* (Petroleum Geo-Services), C. Barros (PGS), E. Hodges (PGS), A. Valenciano (PGS), S. Lu (PGS), N. Chemingui (PGS), P. Johann (Petrobras), E. Thedy (Petrobras)

Summary

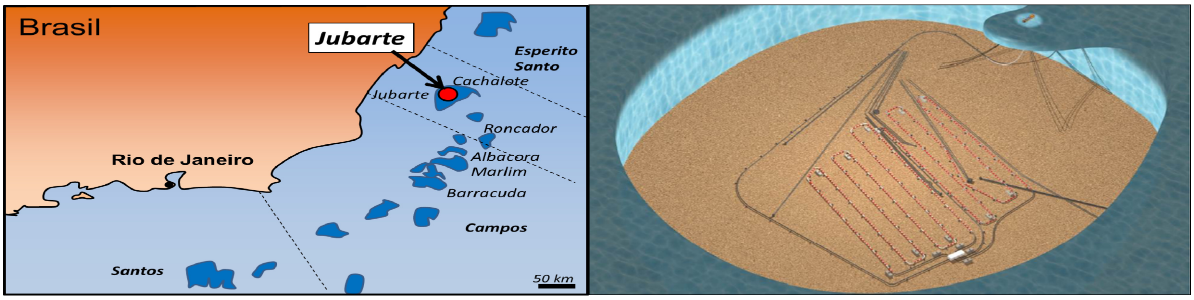
A receiver decimation study has been performed for assessing the potential of using very sparse receiver grids in conjunction with high-order multiple imaging techniques for 4D reservoir monitoring. Reducing the density of receivers in a PRM (permanent reservoir monitoring) system will reduce the capital expenditure. For OBN (ocean bottom node) acquisition, cost saving can be achieve from more effective node deployment. The imaging process makes use of the multiple sea-surface reflections to significantly increase the fold, hence compensating for the reduced number of sensors. We will show that with the above imaging technology it is possible to use 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 taking out receiver included into circular patches within a diameter of 600 m. The number of sensors is then reduced by a factor two. The results demonstrate that it is possible to break some established limit in term of seabed sensor sparseness without compromising the resolution of 3D/4D imaging.

Introduction

Seismic seabed acquisition, such as OBC/OBN, has some benefit for imaging offshore reservoirs when a wide azimuthal illumination is needed or when surface infrastructure obstruction occurs. Such acquisition can offer wide azimuth and long offset illumination with a limited operational constraint for the acoustic source part because the shooting vessel is physically disconnected from the recording system. However, the receiver deployment on the seafloor may require more complex operations, especially in a deep water context. In addition, seabed infrastructure installations (flow line, well head, pump...) 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 is necessary in order to assure a minimum of fold. The receiver sparsity limit for seabed acquisition has been largely commented in the literature. Most of the OBC case studies, using the standard up-going wavefield imaging, have a maximum of 300 m of receiver line separation and 100 m sensor distance along the cable. Beyond these limits, the image suffers 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 examples, 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 a another deep water OBN example, a receiver decimation using a grid of 450 x 450 m receivers has been recommended for preserving the imaging resolution (Olofsson & al., 2012). In any cases, 500 m receiver distance 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 300m. Permanent reservoir monitoring (PRM) installations can be considered as the ultimate solution for detecting small seismic signal variation related to the reservoir production. We simulate the impact of very sparse geometry by creating receiver gaps, larger than the 500 m limit, within the initial 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 km^2 with the primary objective being to validate the fiber optic sensing technology in detecting 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 is made of 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 intervals. The first 4D signals have been 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, but was sufficient for validating the deep-water pilot installation. The quality of the 4D seismic signal demonstrates the high detectability expected from a permanent optical installation.

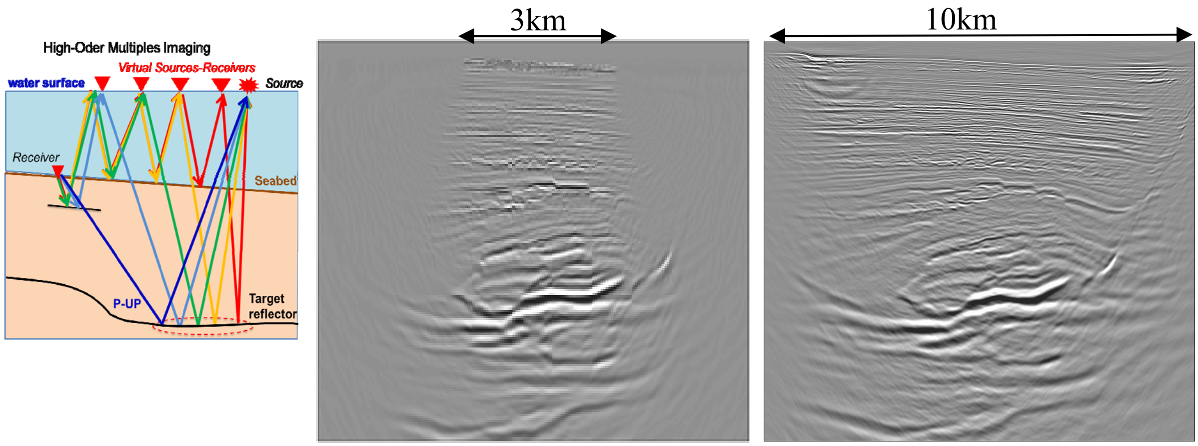


a) b)

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 reflections, primaries 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 receiver array of 3 km while the image using all orders of multiples is defined by the source distribution covering 10 km.

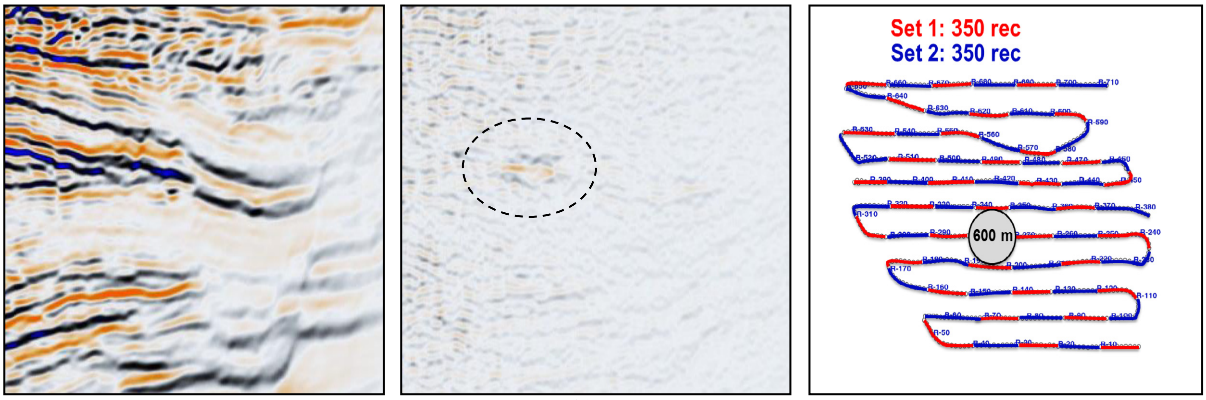


a) b) c)

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 the 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 illumination gain, proportional of the number of orders of multiple present in the record length, we should be able to increase the sparsity of the receivers without impacting too much 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 3c 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). Sections, for each subset, are then separated by 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.

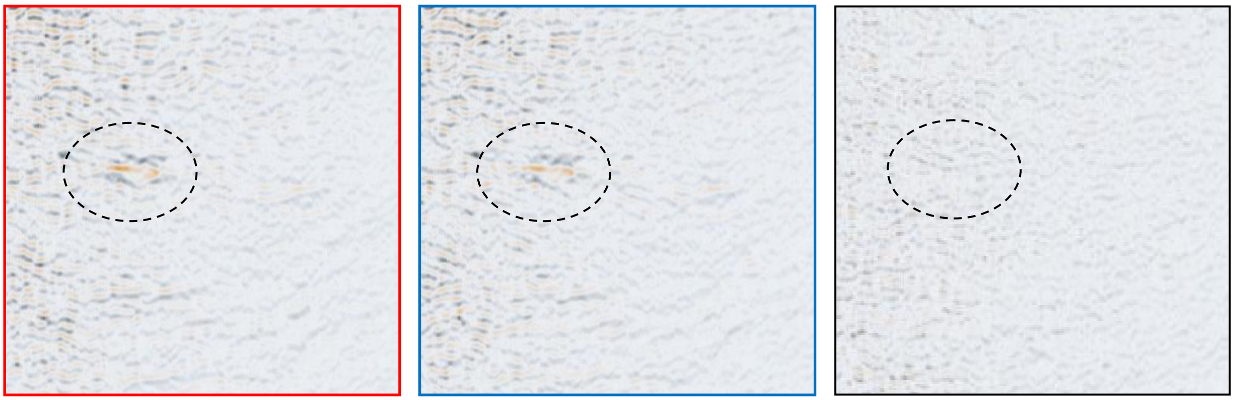


a) b) c)

Figure 3: a) Reference 3D image section using full set of 700 receivers. b) Reference 4D image difference section using full set of 700 receivers. c) 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 doing the difference between two “high order multiple” images from two surveys acquired a year apart. It’s 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. This noise can be handled pre or post migration using cross-equalization filters. The 4D difference interpretation is not the objective of this paper. 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 4 a) and b) 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 receiver gap 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 sharing the same shots.



a) b) c)

Figure 4 a) 4D difference using subset 1(350 rec.), b) 4D difference using subset 2 (350 rec.), c) Difference of the two 4D differences (4D subset1- 4D subset2)

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

Figure 4 c) 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 simple decimation test demonstrates the potential of the “high order multiple imaging” to enable very sparse seabed acquisition. However, the concept of acquisition sparsity should be clarified. This test shows that large sensor gaps can be handled but a minimum of fold has to be respected for assuring a 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, but their location on the seabed is inconsequential or less important. This can have a significant economic impact on the OBC or OBN deployment as larger area can be covered with stretched layout geometry and a reduced number of sensors. Also, seabed infrastructures can be easily 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 very 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 increase significantly 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 is possible to break some established 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 in particularly quiet parts on the seabed thereby improving the detectability of weak 4D signals without compromising the target illumination.

Acknowledgements

Thanks to PETROBRAS for the technology collaboration and permission to publish the data.
Special thanks to Petrobras Rio processing, Petrobras Rio reservoir dept. and Petrobras Vitoria asset.
Thanks also go to the PGS Rio Processing & Reservoir team

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