Advances in Processing Technologies of 4D OBS in Deepwater

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Abstract

Recent advances in methods of seismic processing of time lapse 4D Ocean Bottom Seismic (OBS) have allowed Shell processing to quickly influence well and reservoir management decisions. OBS using nodes or cables has been acquired at more than 15 fields including multiple repeats for 4D time-lapse analyses. We will show some of the advancements in processing technology that have improved the quality and speed of delivery. We present examples from the BC-10 O-North field, where advanced Least Squares Migration (LSM) technologies have been applied to further impact 4D OBS images. We will show that broadband processing techniques that were designed for variable cable depth can recover more signal than first thought possible with standard seismic. The combination of these and other technologies will be required for high-fidelity reservoir monitoring in deepwater Brazil, especially for the large pre-salt carbonate fields where 4D effects are expected to be relatively small.

Introduction

Shell has gained a wide array of experience in the acquisition and rapid processing of 4D OBS. 4D reservoir monitoring is becoming indispensable as a field development tool, by increasing our ability to see what has been produced, bypassed, or where injectors are moving water, gas, or CO_2. The Health, Safety, Security, and Environmental (HSSE) issues are becoming requirements as the monitoring for out of zone injection is expected for regulatory reasons and continued license to operate. The advantages of OBS for time lapse are many including receiver repeatability and high signal to noise ratio which results in achieved NRMS ranges of 3-5% depending on the field and type of the 4D monitoring technology (life-of-field cables or retrievable nodes). Similar NRMS values have been reported by Petrobras at Jubarte (4% NRMS), which utilizes permanent ocean bottom cables (OBC), where the value from OBS systems for field development decisions has been realized (Thedy et al, 2015; Johann et al, 2016).

To date, Shell has acquired and processed over 25 deepwater OBS surveys covering more than 15 fields. Further, it has completed dedicated 4D OBS processing over 5 producing fields that include multiple vintages of OBS monitor surveys. Well established processing flows are in place for rapid repeat processing of these surveys, with initial results usually delivered within a month.

Advances continue to be made with 4D processing, including utilization of Least Squares Migration and broadband processing as we continually push towards improving interpretability.

OBS Survey Design

Ocean Bottom Seismic is any configuration of sensors placed on the seafloor with sea surface shots. The detectors are a combination of hydrophones measuring pressure and 3-component geophones placed in the strata to detect a directional signal. These can be either stand-alone nodes, deployed and later retrieved by a remote operated vehicle (ROV), or life-of-field sensors connected by cables installed on the seafloor.

The location of the sensors and the associated shots are not trivial, especially since the scope of these surveys is generally a small targeted area. The OBS design (Theriot et al, 2014) is optimized to illuminate this area within budget limitations and operational constraints. The design process first uses ray tracing to do quick scenario testing and define the node/shot locations for maximum illumination. Then, a synthetic node gather is created at each of these locations via a velocity perturbation at target events. These synthetic data can then be migrated and each node selectively stacked to determine the minimum required node area for adequate illumination with contribution of each individual node compared to the full stack.

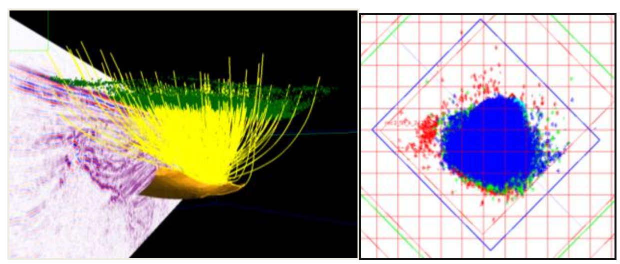

Figure 1 **-** (Left) Surveys are carefully designed to illuminate target events. (Right) The surface locations of these rays dictate the starting node design area.

Advantages of OBS for 4D

For time lapse seismic the advantages of OBS are many, including position repeatability, high fold, multi-azimuths, quiet recording environment, multiple sets of recorded wavefields, and speed of processing. Most importantly is the reduced positional recording differences between the base and monitor acquisitions. Since OBS nodes can be placed within meters of the original position, repeatability errors can be negligible and even zero if nodes remain on the sea floor as in a cabled system. Also, OBS nodes allow us to repeat these locations even if a FPSO or other infrastructure moves in over a well location, whereas a streamer survey would have a larger acquisition hole from the base to the monitor. Additionally, shot repeatability errors are smaller because of a lack of thousands of meters of streamers towed behind the source boat. Acquiring the permitting and managing the logistics of multi-streamers is also more difficult as there is more equipment at risk of entanglement.

OBS is naturally extremely high in fold and often has nearly full azimuths which results in high signal to noise ratios and thus lower NRMS values. The sea floor is a quieter environment compared to the sea surface which results in data free of wave generated receiver noise. The multi component sensors also allow for a recording of different wavefields including the upgoing and downgoing wavefield which can be combined to produce a similarity weighting for additional 4D noise suppression (Hatchell et al, 2012).

Moreover, high quality “fast tracks” can be delivered in less than 4 weeks by using pre-determined processing parametrization. This has proven valuable for not only production optimization but also to ensure immediate safety checks for issues related to shallow geohazard problems, health of injector wells, and other HSSE aspects. Most large 4D changes will be seen even in this fast track result. In 3-6 months a finalized flow is complete with each step carefully optimized to image the subtler 4D signals.

Processing 4D and Advanced Imaging

Over many projects, Shell has improved upon its 3D OBS processing flow (Beal et al, 2014) to optimize each step for time lapse. Among the most important steps are the derivation of highly accurate water velocity/tidal statics and node positioning which are critical to achieve low noise, high quality time lapse images. This derivation is significantly aided by Pressure Inverted Echo Sounder (PIES) units which are deployed on the seafloor during every OBS survey conducted at Shell since 2012 and measure two-way water time to derive water velocity and also measure pressure which can be converted to depth to monitor tidal variations (Wang et al, 2013).

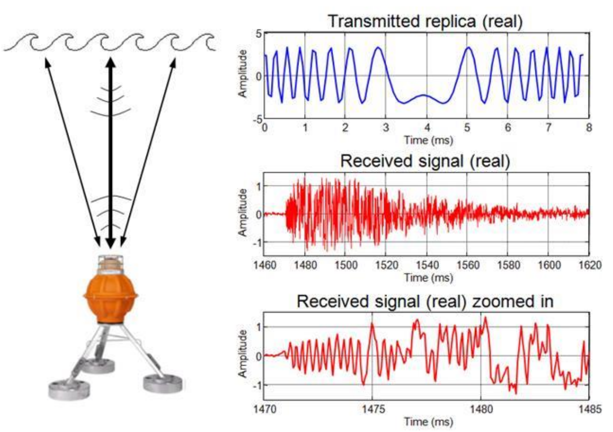

Figure 2 - (Left) A PIES unit deployed at the seafloor (Right) The real component of the modulated signal which will be used to derive water velocity.

OBS surveys are proven to deliver a high confidence 4D signal and generally a fast track 4D volume can be delivered to interpreters for analysis weeks after receiving the recorded data in house. Streamer time lapse surveys, even with repeatable acquisition and the latest processing techniques, tend to result in NRMS repeatability ratios of 15-20%. However, recent OBS surveys co-processed for 4D have regularly resulted in NRMS values around 4-5% and 3% NRMS in the case of the Brazil O-North ocean bottom cable (OBC) installation (Figure 3). This 3-4x reduction in 4D noise over streamer time lapse means that those subtler signals or signals in “difficult to image” areas can now be more clearly interpreted. Further, this new threshold on noise levels could unlock 4D opportunities in fields whose rock and fluid properties indicate subtle impedance changes, which are not feasible to be detected with repeated streamer acquisition. We envision OBS, paired with advanced co-processing, as the technology that is needed to image time lapse signals in the pre-salt areas of Brazil.

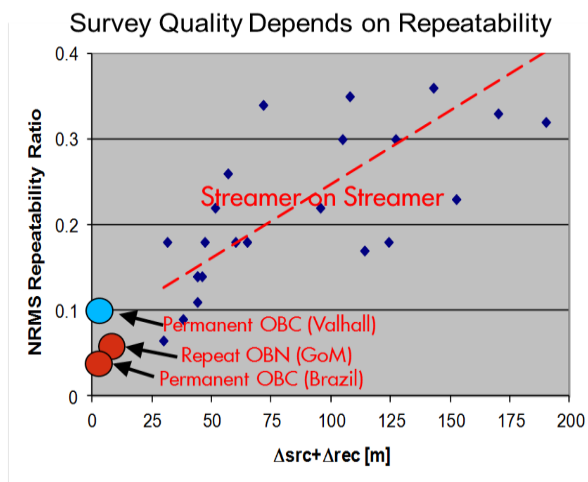

Figure 3 – Cross plot showing relationship between acquisition repeatability and NRMS, a quality metric that calculates the amount of 4D noise.

Shell is conducting continuous improvement of the existing 4D processing toolbox with advanced imaging techniques including least squares migration algorithm (LSM). LSM aims to produce a true amplitude migrated image suitable for quantitative analysis. Another advantage of LSM for 4D applications is compensation of the acquisition irregularities on final subsurface images (Salomons et al, 2014).

Shell has had recent success in applying LSM to OBS data from multiple fields for 4D leading to more reliable quantitative interpretation of the results. This technique has been particularly useful when interpreting in the substack domain. Figure 4 demonstrates suppression of swing noises in angle-azimuth gathers of a Kirchhoff migration with 10 iterations of Kirchhoff LSM. This reduced noise will lead to more reliable quantitative interpretation of time lapse changes in the pre-stack domain.

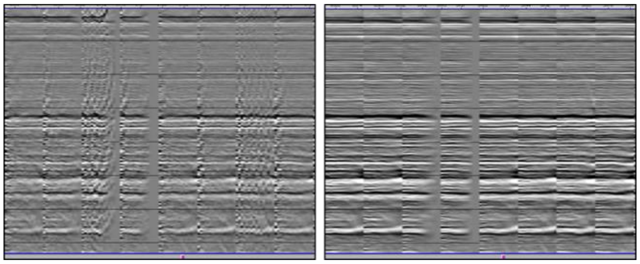

Figure 4 - (Left) Angle-azimuth gathers after standard Kirchhoff. (Right) Angle-azimuth gathers after 10 iterations of Kirchhoff LSM.

Low Cost 4D OBS

While Shell has high confidence in using the ocean bottom seismic technology, it is recognized that OBS has a higher per unit cost than streamer acquisition. The frequency of 4D marine seismic surveys and ease of their deployment is often limited by costs and footprint of acquisition. There is a need to monitor deepwater producing fields more frequently and on-demand to ensure the efficiency and safety of operations. For fields using nodes, the concept of “Instantaneous 4D (i4D)” was developed as a monitoring strategy for fast changing time lapse effects such as those around injection wells (Hatchell et al, 2013). These are surveys with only a fraction of the total number of nodes used in a full field survey and smaller shot patches which specifically target high risk, high-cost wells, typically water injectors. The idea is to acquire i4D surveys at a more frequent rate and at a lower cost than a full field survey. Due to the high repeatability of OBS, these smaller surveys still yield clear 4D signals in the areas they image.

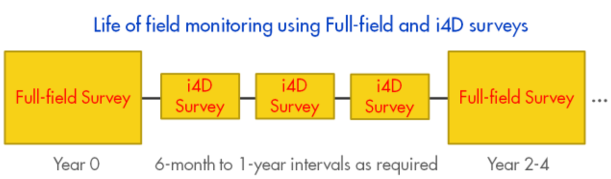

Figure 5 - Timeline of a monitoring strategy that employs i4D surveys between the full-field acquisitions.

While i4D surveys shrink the size of the image area, there is another option that may reduce cost by decimating nodes. Wang et al (2013) discusses node decimations effects on 4D signals. He concludes that good quality time lapse data can be achieved by using only ½ to ¼ of the original number of nodes utilized in the full field survey. We see the application of LSM to these decimated surveys as an enabler to reduce sparse acquisition noise even further (Salomons et al, 2014).

In today’s oil price environment, value vs. cost implications are more important than ever. The life of field monitoring cycle shown in Figure 5 can further be refined to combine OBS monitoring with other monitoring solutions. This is discussed in more detail by Chalenski et al (2016) and Lopez et al (2017).

Qualitative 4D

OBS surveys are not always acquired before production to give a true 4D baseline. However, there is usually a legacy towed streamer survey that was acquired first. The term “Qualitative 4D” is used to describe efforts to attain time lapse information between these legacy streamer surveys and a more recent full-azimuth OBS survey. As the ray paths between the different acquisition methods are quite different, considerable care must be taken when doing this type of analysis. Theriot et al (2015) describes a method of image domain scaling which has led to high quality results. Amplitude changes caused by different acquisition types tend to be slowly varying in the subsurface angle (azimuth) domain, and scalars can therefore be derived to remove these effects. However, since 4D data quality is always based on the repeatability of the surveys, the result will not be as clear compared to the dedicated acquisition. However, under certain rock and fluid conditions, Qualitative 4D processing has produced high quality 4D signals. In this case, prior feasibility study is a key to understand the expected acoustic impedance changes relative to the forecasted NRMS noise level. An example of the measured impedance change resulting from a Qualitative 4D processing project is shown on Figure 6.

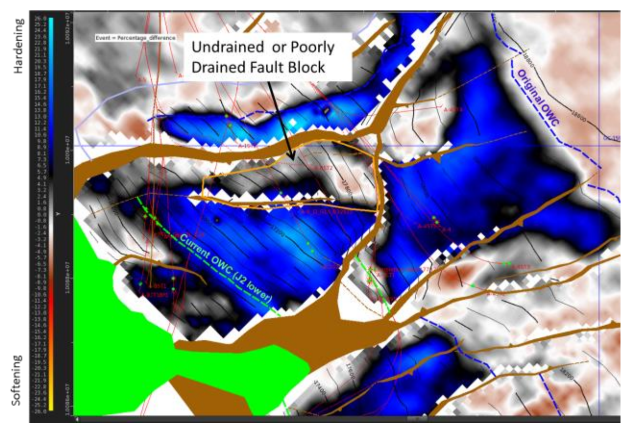

Figure 6 **-** Map showing % impedance change in an OBS-Streamer 4D. The hardening (blue) indicates the water swept area. Fault block with no 4D changes represents a possible infill opportunity.

Broadband Processing

Broadband processing has made advances in recent years to deal with the angular nature of the ghost problem. This technology was developed to properly deghost non-flat cable data (Soubaras et al, 2010), but Shell has found advantages to applying it to flat streamer data and OBS.

It is well known that the ghost interference is a common occurence of marine data on the source or receiver side. This ghost is the energy that is reflected at the sea surface between the surface and the depth of the receiver or shot. The ghost signal interferes with the primary signal, producing a distorted signal by compressing the spectrum with variable notches as the angle changes with offset. This is particularly difficult to deal with when the depth of source or receiver is relatively shallow, as the time delay of the ghost is insufficient to separate it from the primary signal. In OBS we are still not free of the problem as there is still a ghost on the shot side.

Because ghosts distort the primary signal, they reduce the value of the resulting seismic data. Therefore, it is common to undertake various techniques to reduce the effect of ghosts. The key element in broadband seismic processing is to attenuate ghosts associated with primary signal. Such ghosts create side lobes on seismic wavelets and jeopardize seismic resolution. This eventually creates difficulty when doing well tie analysis and quantitative interpretation.

The difficulty in dealing with ghosts is that they travel through the earth along the similar path as primary signal, which varies in x-y-z dimensions. The Shell geophysical community developed its own deghosting methodology. The technology is appropriate for both streamer surveys (NAZ or WAZ) and OBS or OBN surveys. It's applicable to receiver deghosting and source deghosting.

Shell has developed deghosting technique that provide at least three advantages:

• It does not require sources or receivers to sit at regular spacing.

• It can be applied to acquisition systems in which the depth of the receivers varies.

• It is fully 3-dimensional, i.e. it accounts for waves whose propagation direction has a horizontal component as well as orthogonal component.

These broadband applications are necessary to sharpen the wavelet for accurate interpretation of thin beds, qualitative interpretation including well ties and amplitude versus offset analysis. The increased spectrum on the low end ensures accurate well ties as thick layers can be resolved in the seismic. Imaging complex areas with steeply dipping events, such as salt walls becomes much more clear with a broadened spectrum. As well, extending the spectrum to the lower end is highly beneficial for further FWI work.

For 4D the angle dependence is also a repeatability issue. Even if the base and monitor surveys are shot in the same "direction", the actual boat passes may be in different directions. Source arrays have significant directionality (and may even be asymmetrical in the fore/aft sense). Oftentimes, the detailed array design changes from base to monitor. Finally, the position of the guns within arrays can vary due to crabbing, and there are other kinds of acquisition variations, such as gun dropouts and water temperature and salinity (which can change bubble periods). So ideally, we need a depulsing algorithm which accounts for all angle dependent effects on the source and receiver side, and which can also vary by shot to take care of all of the forms of shot non-repeatability as mentioned above.

4D OBS Examples

The Shell portfolio includes successful, high quality 4D signals from both types of OBS monitoring solutions: life-of-field cables and nodes. The decision of which system to use highly depends on the specifics of the given field/project: development life, expected signal strength, HSSE risk, injection, vendor availability, country requirements, etc. and must be valued against cost.

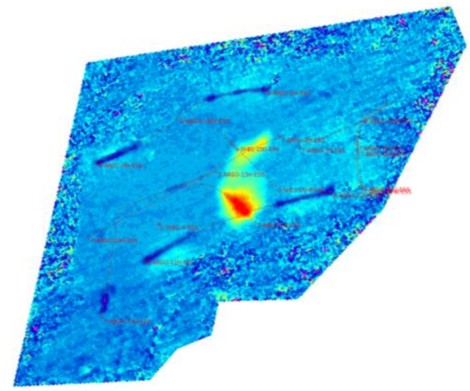

Figure 7 - Clear 4D signal from an ocean bottom cable survey on a 400x100m sensor configuration in Brazil.

The current section will highlight a few 4D results; all processed internally by Shell, from different fields with available 4D data. The first example is related to the life-of-field cable system installation over the BC-10 development in Brazil. This system uses a 400 m x100 m sensor configuration of around 1000 nodes and is monitored roughly once a year to monitor water injection. In fields such as this, consistent monitoring for fluid movement and "gas out of solution" signals is important for efficient management of the water injection rates. A clear 4D signal from one of these time steps is shown in Figure 7 (for more 4D results at BC10 field refer to Galarraga et al, 2015). Additionally, this survey has deployed Kirchhoff LSM as part of the project that has resulted in lower noise and detection of subtler time lapse signals.

The second example features an i4D nodal survey that was acquired in deepwater Gulf of Mexico. World class 4D hardening signal caused by the water injection is displayed in Figure 8. It has been detected subsalt by using only 125 carefully designed nodes during the data acquisition.

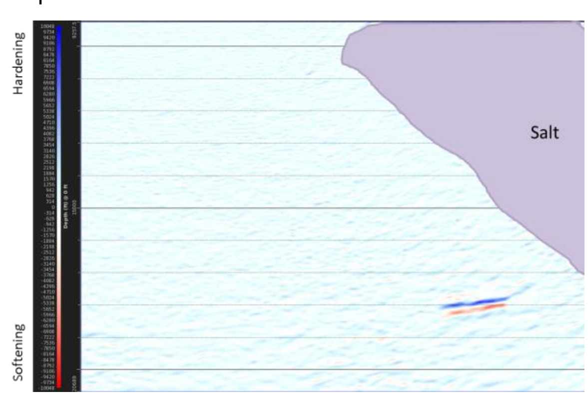

Figure 8 - Subsalt 4D amplitude difference signal has been achieved with OBS data for an i4D survey.

The last result highlights the denoising technique via similarity weighting previously referenced (Hatchell et al, 2012) in a development field in the Gulf of Mexico. Upgoing and downgoing wavefield 4D amplitude differences clearly show multiple 4D signals throughout the section. These differences can simply be stacked together to reduce noise. However, even more noise can be suppressed by stacking with a weighting scheme that attenuates parts of the section that are different between the upgoing and downgoing wavefields (Figure 9) thus resulting in even lower achieved NRMS values compared to downgoing and upgoing waves alone.

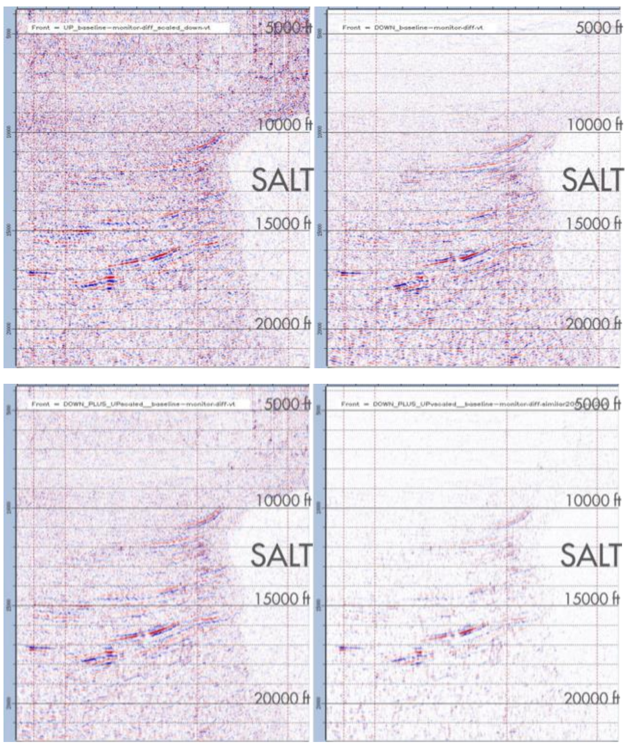

Figure 9 - (Top left) Upgoing wavefield 4D amplitude difference volume. (Top right) Downgoing wavefield 4D amplitude difference volume. (Bottom left) Stack of the upgoing and downgoing wavefield 4D differences volumes. (Bottom right) Stack of the upgoing and downgoing wavefield 4D differences volumes with the similarity weighting scheme applied.

Conclusions

4D OBS has proven to be a critical surveillance method for optimal field development and HSSE. These advanced processing methods of 4D OBS, including LSM and use of broadband technologies are moving into Shell's standard production flows. As our processing methods become more robust we see noise values continue to decrease, lateral resolution increases, and frequencies broaden. We believe that utilization of 4D OBS and use of advanced processing methods is appropriate technology for Brazil especially in the difficult areas such as the pre-salt. We hope to encourage more OBS surveys early on so as to establish solid baselines for future 4D work in development fields in Brazil.

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