

Onshore monitoring with Virtual Source seismic in horizontal wells: challenges and solutions

Andrey Bakulin*, Jorge Lopez, Indrani Sinha Herhold, Albena Mateeva, Shell International E & P Inc.

Summary

The Virtual Source (VS) Method provides unparalleled capability to synthesize controlled and repeatable downhole sources at the location of VSP geophones. Although the physical sources are located at the surface, VS redatuming corrects for small non-repeatability of surface shooting and compensates for subsurface changes above the receivers. If Virtual Sources are created at permanently placed receivers, then we essentially obtain a “permanent downhole source and receiver” configuration that is optimal for sensitive reservoir monitoring. We demonstrate these advantages with a field data example and then focus on defining acquisition, drilling and tool requirements for onshore VS monitoring.

Introduction

Strong demand and high oil prices have led to greatly increased emphasis on enhanced oil recovery (EOR). Successful reservoir management while executing EOR benefits from sensitive and repeatable seismic monitoring. Unfortunately, typical complex near-surface conditions, seasonal changes, and variation of shooting geometry between surveys fundamentally limit the sensitivity and resolution of surface 4D seismic. Virtual Source monitoring is able to mitigate most of these factors provided downhole recording is done below the zone of biggest complexity and below the zone of seasonal changes.

The Virtual Source Method (Bakulin and Calvert, 2004, 2006) performs time-reversal redatuming of surface shots to the location of downhole geophones (Figure 1). From a processing standpoint it suffices to visualize the technique as a cross-correlation of direct-arrival energy at one buried geophone (the ‘Virtual Source’) with the trace recorded at a second geophone (the receiver). The result, once summed

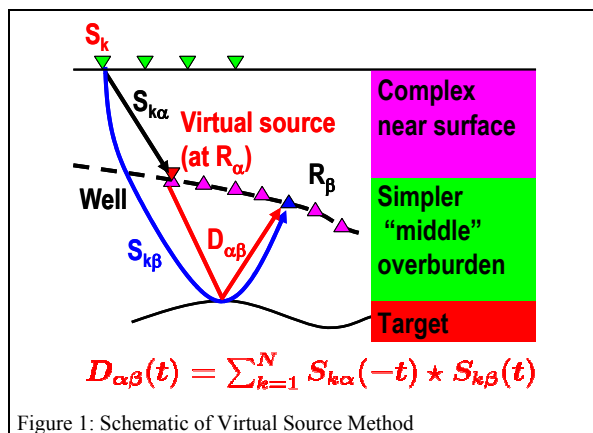


Figure 1: Schematic of Virtual Source Method

over a suitable set of illuminating physical sources, approximates the response of a buried source-receiver pair in the subsurface. Since the data-driven VS redatuming process does not require any velocity information, VS monitoring has emerged as a complementary tool to conventional time-lapse seismic to address the following challenges:

- Inability to repeat the acquisition geometry (e.g., source and receiver locations)
- False 4D responses due to seasonal changes in the near surface between time-lapse surveys that can be completely overwhelming in certain areas (e.g., Arctic, Siberia, etc)
- Difficulty in tracking small time-lapse signals under complex near surface (typical for Middle East reservoirs)

In-situ 4D seismic

In the past it was believed that the major source of non-repeatability was due to poor repetition of acquisition geometry (Calvert, 2005). Attempts to repeat the geometry as much as practical revealed that geometry is only part of the problem. Indeed, even with permanent geophones and permanent shot locations it became clear that both surface source coupling and near-surface can change rapidly with time (Meunier, 2000; Bakulin and Calvert, 2004, 2006; Bianchi et al., 2005; Faure and Spitz, 2006). Attempts to bury geophones led to improved results but left untouched the non-repeatability on the source side. The ultimate answer to the repeatability problem is “in-situ 4D seismic” (Bakulin et al., 2000) with sources and receivers placed at fixed locations beneath the layer subject to seasonal changes and beneath the most overburden troubles. There are two ways to implement in-situ 4D seismic:

- Bury both sources and receivers
- Bury receivers only and create downhole Virtual Sources using surface shots.

We expect both methods to be useful depending on the circumstances. The first method is preferred when surface facilities prevent us from shooting, as is the case for many mature fields or when seasonal changes are very large. Seismic experiments (Meunier, 2000; Bianchi et al., 2005; Faure and Spitz, 2006) implemented this method with buried piezoelectric sources and permanent borehole receivers. Excellent repeatability was achieved and tiny time-lapse signals have been observed. While this version of in-situ 4D seismic is attractive due to the best possible repeatability, it has its limits:

- It is practical to deploy permanent sources at shallow depths (~10-50 m), thus if overburden complexity is present below the sources it will hamper the 4D signal.
- It is costly to have many permanent sources, thus areal coverage will tend to be sparse.

Virtual Source seismic in horizontal wells

The alternative way to achieve a buried and fixed source-receiver configuration is by the Virtual Source Method, where only the receivers are actually buried, which makes it more economical. The advantages of this approach are (Bakulin and Calvert, 2004, 2006; Bakulin et al, 2007b):

- VS corrects for typical non-repeatability of surface shots and seasonal changes
- Receivers (and thus VS's) can be placed below overburden complexity inside boreholes and VS method can remove damaging overburden effects
- Receivers are easier to deploy than sources in multiple wells to achieve areal coverage
- Directional *P* and *S* sources can be manufactured from the same surface shooting
- In-situ seismic can be generated in production and injection wells with permanent receiver strings.

The remaining disadvantages are:

- Multiple shots at the surface are required to create a single Virtual Source at depth (access issues)
- Time-reversal correction for seasonal changes is not as good as with actual downhole sources.

Here we concentrate on VS monitoring applied to land conditions where dedicated observation wells are affordable. Similar concept applies to offshore environment and Mehta et al (2007b) demonstrate advantages of VS monitoring with marine ocean-bottom cables.

Peace River example

Let us start with a real data example from Peace River, where massive heavy oil resources are being exploited by cyclic steam stimulation. Studies show that the steam paths in the reservoir are hard to model and must be measured to be able to alter the steam injection patterns to increase recovery from each square-kilometer development pad. Glacial channels overlying the field and seasonal changes in the immediate near surface (Figure 2), compromise data quality and repeatability of surface seismic and make us seek downhole solutions with Virtual Source monitoring. At Pad 40, a well was drilled above the reservoir at 45° inclination and instrumented with 50 permanent 3C geophones. The seismic datasets include a baseline and four repeats of a 2D source line at various stages of the steam injection cycle, with simultaneous surface and downhole recording. We have processed the downhole data to synthesize Virtual Sources at each receiver location and focused our attention on the up-going, zero-offset Virtual Source reflections. This basic single-fold dataset ties the corresponding surface seismic and shows increased resolution of the 75m seal section, the 25m reservoir, and the unconformity below. The single-fold Virtual Source time-lapse images (Figure 2) show good repeatability above the reservoir and distinct changes in the reservoir and the section below. While repeatability of single-fold VS seismic may not be as good as for a downhole source, it

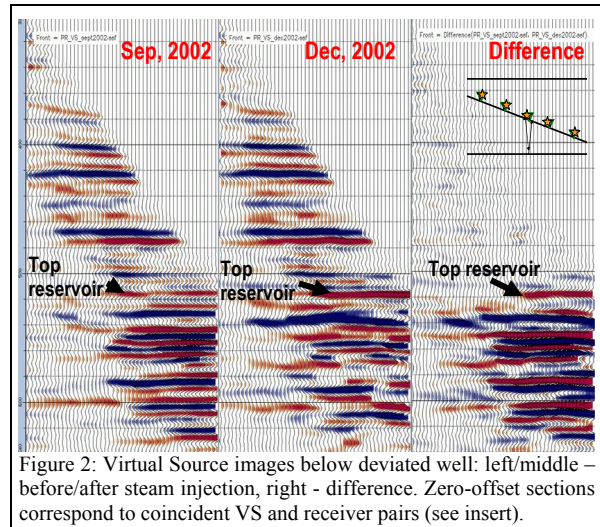


Figure 2: Virtual Source images below deviated well: left/middle – before/after steam injection, right - difference. Zero-offset sections correspond to coincident VS and receiver pairs (see insert).

is better than repeatability of a full-fold stacked surface seismic. This is mainly because the Virtual Source Method bypasses overburden complexities and largely corrects for seasonal changes. Further improvement can be achieved by generating offset VS seismic and stacking it (Bakulin and Calvert, 2004, 2006). A quantitative evaluation of the changes over time will be attempted, although the results will be of limited use given the small imaged area and an apparent shadow zone near the edge of the survey. However, these encouraging results justify a test of areal monitoring, as we discuss below.

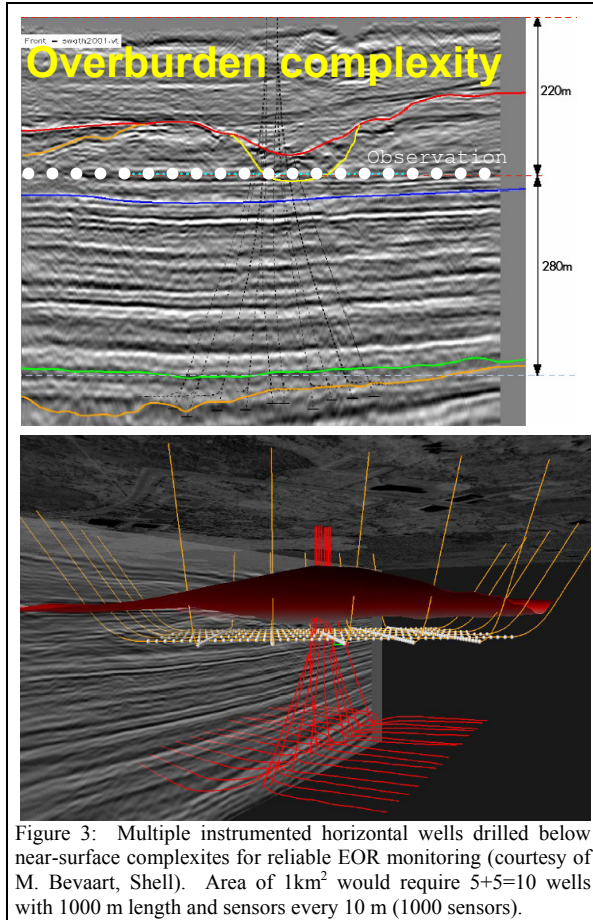
Monitoring on land

Building on this data example we observe these typical features for many of the Shell's land assets:

- Relatively shallow targets
- Poor quality of surface seismic with ground-roll and refractions dominating the data (surface effects)
- Challenging near surface and/or overburden
- Seasonal changes and variation in source coupling

Unlike the Peace River example, time-lapse signals are often of very small magnitude (Middle East, US onshore) due to tight rocks or small contrasts (water-oil, gas-steam). We expect that receivers placed as shallow as tens of meters to several hundreds of meters would be able to mitigate most of the unfavorable conditions and allow sensitive 4D monitoring with Virtual Sources. While for very shallow depths one can place single sensors in individual vertical holes, this becomes less practical with depth and multiple instrumented horizontal or deviated observation wells are preferable. A field-wide monitoring solution is illustrated in Figure 3 with a grid of horizontal wells over the producing area. The simplest case of areal monitoring requires only two orthogonal wells (Virtual Cross-Spread). Monitoring with Virtual Sources in observation wells is technically feasible with current

Virtual Source seismic in horizontal wells



technology for single instrumented well bores. For field-wide areal monitoring, multiple instrumented well bores are required and several technical and operational challenges need to be overcome.

Drilling challenges

First and foremost, we need to nurture inexpensive and reliable methods for drilling horizontal wells in the shallow and deep overburden. A recent U.S. Department of Energy initiative fostered the development of a set of low-cost drilling technologies for vertical, instrumented, very small diameter “microholes”. A similar effort is required for horizontal wells to fully leverage the Virtual Source Method. A cost of less than \$100K per well (Figure 3) is desired to make a field-wide monitoring attractive. U-shaped wells (with two surface exits) are particularly attractive for shallow horizontal wells, since they provide greatest flexibility for sensor deployment.

For shallow applications, it is most practical to have an open hole because:

- Casing and cementing will increase the cost

- Cementing horizontal wells is difficult and a poor cement job will invalidate geophone responses.

In some cases it may be appropriate to case and cement wells up to the horizontal section.

Borehole seismic sensors

Fit-for-purpose seismic sensor arrays need to become available for this new geophysical market niche. We strongly advocate the use of 4C arrays to allow routine application of dual-sensor (vertical geophone + hydrophone) wavefield separation for improved VS seismic (Mehta et al., 2007a). Wireline VSP sensors are designed for very harsh pressure and temperature conditions, and provide good borehole coupling. Their specs are well above those needed for shallow wells. Their cost (\$25-40K per station) is not attractive for permanent deployment. A much cheaper option (\$4-5K per station) is represented by the fit-for-purpose shallow VSP arrays shown in Figure 4. To make a field-wide solution (Figure 3) attractive, a cost of ~\$1K per sensor needs to be achieved. Typical surface seismic arrays may have the right specs, but are not yet suitable for deployment in horizontal wells. Ocean-bottom cables (\$7-10K per station) represent another alternative with already built-in hydrophone sensors. It is expected that they can be used without modification in horizontal wells, although some simplification and adaptation to borehole conditions may be beneficial. Alternatively, re-packaging of surface seismic arrays (a la OBC) may allow them to adapt to borehole coupling conditions. Long sensor arrays would also require digital recording and transmission systems (fiber optics).



Figure 4: 4C sensor from VSP array for shallow boreholes (courtesy of Don Fussell, VCable LLC).

Conveyance methods

Reliable and cheap conveyance methods need to be developed to deploy long seismic arrays in horizontal or deviated wells. Our initial ranking of the suitable methods is as follows:

- Pulling array behind drill string in U-shaped well
- Packing array inside coiled tubing
- Deploying array inside the drill pipe and then pulling the drillpipe out
- Tubing (casing)-conveyed seismic array that is later cemented in place (typically on the outside)

Next we discuss top two options in some detail.

Virtual Source seismic in horizontal wells

U-shaped well

For shallow depths U-shaped wells provide the greatest reliability and robustness in cable deployment (Figure 5). The seismic cable is simply pulled behind the drillstring while access remains at both ends. Indeed, the so-called Horizontal Directional Drilling (Willoughby, 2005) is an exploding industry due to increased restrictions to surface access and environmental factors. Only the pilot hole is required for a seismic cable and thus the pre-reaming step is eliminated (Figure 5). Even safer is to deploy the cable

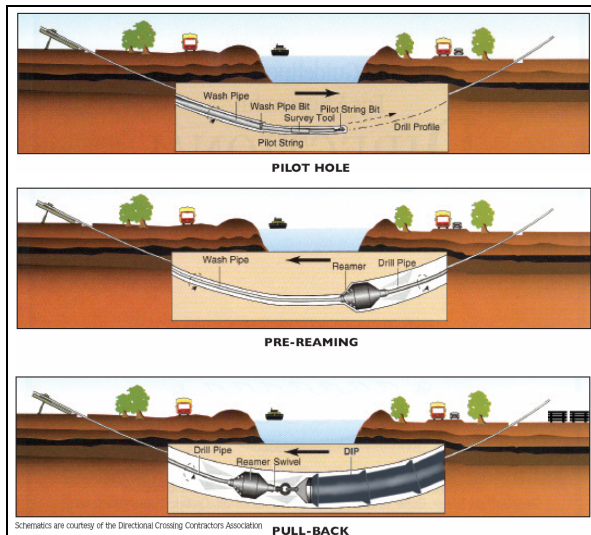


Figure 5: Schematics of Horizontal Directional Drilling beneath a river (from www.dipra.org).

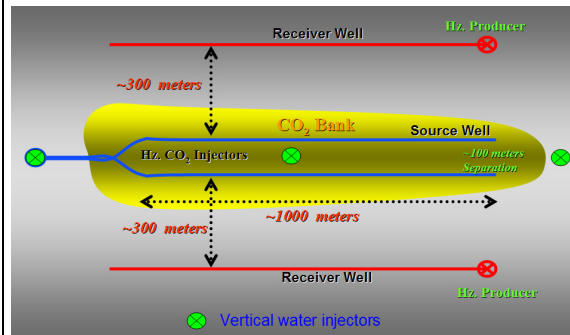


Figure 6: Horizontal cross-well survey performed with hydrophone array inside coiled tubing (courtesy of Ernie Majer, LBNL).

first inside the drillpipe and then pull the drillpipe out of the hole. This would be best to protect the seismic cable provided that cable twisting can be counteracted.

Seismic array inside coiled tubing

When U-shaped wells are no longer possible due to depth and other constraints, we envision another method to take

place in conventional horizontal boreholes. Pre-packing seismic arrays inside coiled tubing has been reported for surveys with hydrophone arrays. Figure 6 depicts the Weyburn survey (Majer et al., 2001) where both sources and receivers were deployed in horizontal wells using coiled tubing. While good hydrophone coupling is achieved by fluid inflow of both the coiled tubing and the borehole, the performance of 3C geophones is not guaranteed. Recording inside the drillpipe in horizontal wells is claimed to produce good results (PipeSeis, 2007) but horizontal components are not discussed. Helical buckling (Cunha, 2004) is expected to provide some contact between the coiled tubing and the formation for any well deviation, but the extent of individual sensor coupling is unknown. Limited experiments show that poor data quality tends to occur when coil tubing with geophones is deployed in vertical holes because the coil tubing does not always contact the hole (Ernie Majer, personal communication, 2007). Therefore proper yard/field tests are required to assess this option. For permanent deployment we advocate “cementing” of the coiled tubing in place by means of Shell’s Universal Fluid (Nahm et al., 1994) that is used as a drilling fluid but later turns into solid material (Figure 7).

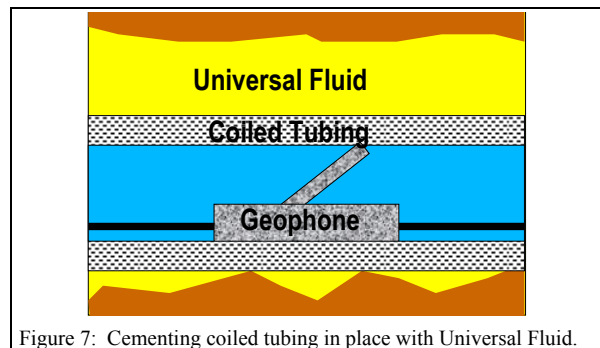


Figure 7: Cementing coiled tubing in place with Universal Fluid.

Conclusions

Virtual Source seismic in horizontal or deviated wells has the potential to revolutionize the Oil & Gas Industry’s ability to image and monitor the subsurface, especially in areas overlain by very complex overburden. The Shell Group is planning and executing field trials to demonstrate that. The ability to cheaply drill and instrument such observation wells is critical to the success of the field-wide monitoring with Virtual Source seismic.

Acknowledgements

We thank the following geophysical contractors for useful discussions: OYO Geospace, VCable, Z-Seis, Schlumberger, PGS, and VSFusion. We are grateful to Ernie Majer (LBNL) for advice. We thank Shell for permission to publish this paper.

EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2007 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

- Bakulin, A., and R. Calvert, 2004, Virtual source: New method for imaging and 4D below complex overburden: 74th Annual International Meeting, SEG, Expanded Abstracts, 2477–2480.
- , 2006, The virtual source method: Theory and case study: *Geophysics*, 71, no. 4, SI139–SI150.
- Bakulin, A., N. Drinkwater, C. Signer, S. Ryan, and A. O'Donovan, 2000, Combining 4D seismic and reservoir simulation - key to effective reservoir management: 62nd Annual Conference and Exhibition, EAGE, Extended Abstracts, B-31.
- Bakulin, A., A. Mateeva, R. Calvert, P. Jorgensen, and J. Lopez, 2007b, Virtual shear source makes shear waves with airguns: *Geophysics*, 72, no. 2, A7–A11.
- Bakulin, A., A. Mateeva, K. Mehta, P. Jorgensen, J. Ferrandis, I. Sinha Herhold, and J. Lopez, 2007a, Virtual source applications to imaging and reservoir monitoring: *The Leading Edge*, 26, 732–740.
- Bianchi, T., J. Meunier, P. Lanfranchi, F. Huguet, and J. Bruneau, 2005, Acquisition and processing challenges in continuous active reservoir monitoring: 2nd North African/Mediterranean Petroleum and Geosciences Conference and Exhibition, Expanded Abstract, P29.
- Calvert, R., 2005, Insights and methods for 4D reservoir monitoring and characterization: SEG/EAGE Distinguished Instructor Series, No. 8.
- Cunha, J. C. , 2004, Buckling of tubulars inside wellbores: A review on recent theoretical and experimental works: *Society for Petroleum Engineers Drilling and Completion*, 19, 1.
- Faure, P., and S. Spitz, 2006, Onshore 4D seismic repeatability at the gas storage geophysical laboratory: 76th Annual International Meeting, SEG, Expanded Abstracts, 3175–3179.
- Majer, E., T. Davis, R. Benson, G. Li, R. Coates, V. Korneev, and L. Walter, 2001, Integration of high resolution borehole seismic data with multi-component 3D surface seismic data for cost effective reservoir recovery: 63rd Annual Conference and Exhibition, EAGE, Extended Abstracts, F-24.
- Mehta, K., A. Bakulin, J. Sheiman, R. Calvert, and R. Snieder, 2007a, Improving the virtual source method by wavefield separation: 77th Annual International Meeting, SEG, Expanded Abstracts.
- Mehta, K., J. Sheiman, R. Snieder, and R. Calvert, 2007b, The virtual source method applied to Mars field OBC data for time-lapse monitoring: 77th Annual International Meeting, SEG, Expanded Abstracts.
- Meunier, J., 2000, A new seismic look at reservoir monitoring: 62nd Annual Conference and Exhibition, EAGE, Extended Abstracts, A-9.
- Nahm, J. J., R. N.Romero, R. E.Wyant, A. A.Hale, B. R. Briggs, T. R. Smith, M. A. Lombardi, and C. R.Keedy, 1994, Universal fluid: A drilling fluid to reduce lost circulation and improve cementing: *Society for Petroleum Engineers Drilling Conference*, 27448-MS.
- PipeSeis, 2007, http://www.vsfusion.com/instrumentation/instrument_pipeseis.htm, accessed April 2, 2007.
- Willoughby, D., 2005, *Horizontal directional drilling: Utility and pipeline applications*: McGraw-Hill.