Virtual Source Method: overview of history and development

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Summary

Rodney Calvert and myself pioneered the Virtual Source Method (VSM) at Shell's Bellaire Technology Center. During 2001-2006 we developed VSM with our colleagues into a viable technique and Shell obtained an early patent on it. We have been influenced by impressive experimental work of Prof. Fink's group that utilized time-reversal acoustics for various focusing applications. We figured out that after focusing at a receiver the time-reversed propagation repeats the forward propagation as if the wavefield was emitted from a Virtual Source at this point. It was nicely illustrated by de Rosny and Fink movie that came along at the right time. Once time-reversal connection was in place – many applications became clear: imaging below complex overburden, monitoring below changing near surface, Virtual Shear Source etc. In this abstract we present an overview of the development of the Virtual Source Method

Introduction

The Virtual Source Method (VSM) was invented as a response to challenges in seismic imaging of complex terrains. We realized that a new leap could not come from improving mature conventional surface seismic imaging. Therefore we decided to attack the problem from the acquisition side. We place the receivers below the most complex part of the overburden (Figure 1), shoot at the surface and then apply a time-reversal technique that undoes all the transmission effects of the near surface without knowing the velocity model. Each receiver is turned into a Virtual Source (VS) thus the name of the technique. Note that downhole acquisition allows one to completely eliminate near-surface velocity model building which is the weakest link in conventional surface imaging.

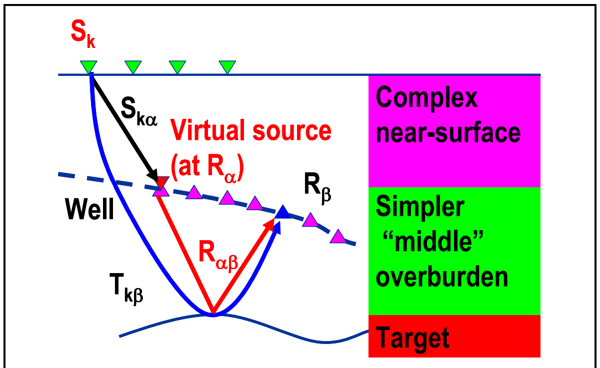

Figure 1: Virtual Source experiment: receivers in the borehole record both downgoing wavefield through the heterogeneous near-surface (black arrow) as well as reflected signal from the deeper targets (red arrow).

History

The Virtual Source Method was inspired by impressive experimental work of Prof. Fink's group on time-reversal acoustics. Figure 2a shows a forward experiment when a source excites a seismic signal and waves propagate in all directions reaching a receiver array on a closed surface. Time reversal ensures that the same wave motion can be reproduced in reverse time if each of the receivers is converted into a source and emits the recorded wavefield in time-reversed chronology (Figure 2b). Time-reversed signal gives rise to the waves that travel to and collapse exactly at the receiver placed in the location of the original source (de Rosny and Fink, 2002). Fink and Prada (2001) describe great many focusing applications utilizing time reversal. Our contribution was to figure out that after collapsing into the source energy is re-radiated again as if a Virtual Source acted at this location (Figure 2c). It may sound trivial now but then little was understood about what happens after focusing (Figure 2b).

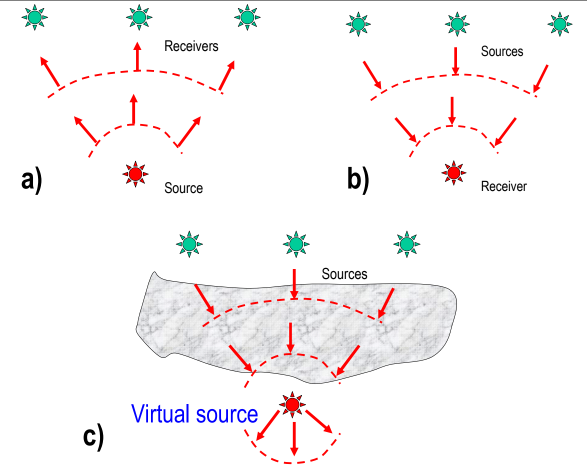

Figure 2: Simple experiment with forward (a) and reverse (b) wave propagation explaining time reversal; (c) Virtual Souce Method as a continuation of the time reversal idea.

Once this time-reversal understanding was in place two important applications became clear: imaging below complex overburden and monitoring below changing near surface. By the middle of 2002 these two applications were thoroughly tested on synthetic elastic models and presented at internal Shell conferences. Figure 3 shows a short summary of these results with the model, very complicated input data, simple Virtual Source gathers after redatuming and good-quality VS images. Conventional surface imaging can only obtain similar results if the exact velocity model would have been known (Figure 3e) which is not a realistic scenario. Patent (Calvert, 2004) was filed in September 2002. Summary of all the findings have been presented in extensive internal Shell report in January of 2003. Shortly after, we made a first real-data application of the VSM on a Peace River VSP dataset and presented the results at Shell 2003 Geophysical Conference. In 2004 these findings became known externally with a presentations at EAGE (Calvert et al, 2004) and SEG (Bakulin and Calvert, 2004) and external Geophysics paper (Bakulin and Calvert, 2006). Connection of VSM to modified Kirchhoff-Helmholtz integral was pointed by Korneev and Bakulin (2006). Let us review major milestones of the VSM.

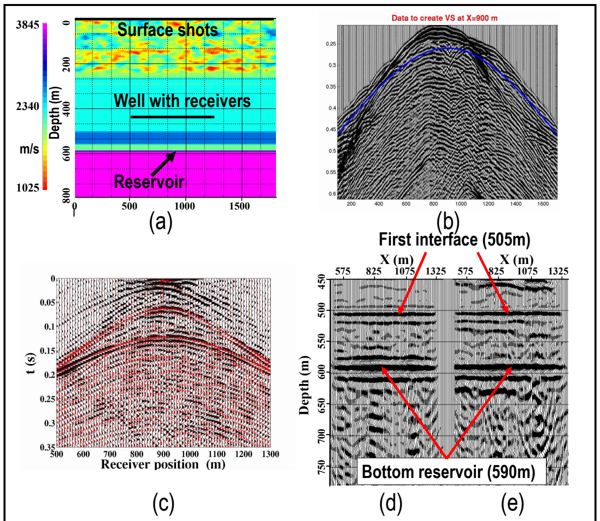

Figure 3: Synthetic Peace River model to image through complex overburden with virtual source technology: (a) P-wave velocity model with very heterogeneous near-surface layer; (b) common-receiver gather showing great distortions of the VSP wavefield; (c) common virtual source gather (red) compared to ground truth response of buried source (black); (d) VS image obtained with 1D velocity model beneath the well; (e) image of VSP data assuming unrealistic scenario where exact near-surface velocity model is known

Time gating and downward radiation

At the very beginning we figured that time-reversing the entire wavefield was not a good idea in realistic applications with only one-sided surface illumination. We wanted Virtual Source to radiate only down or only towards the target and we wanted to feed it with only P-wave energy for P-wave imaging. We recognized early on that one-sided illumination is beneficial to create only downward radiation as shown by Figure 2c. We also realized that best feeding energy for P-wave imaging comes from first arrivals. Therefore our initial best practice consisted in cross-correlating wavefield gated in first arrivals with ungated wavefield (Bakulin and Calvert, 2004, 2006).

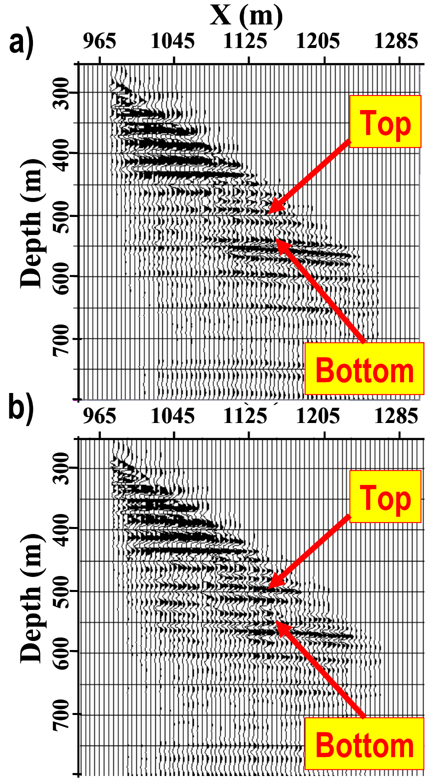

Figure 4: Monitroing with Virtual Sources in well deviated at 45 degrees. VSP data from Peace River: a) baseline image before steam injection; b) image after steam injection. Note strong time-lapse signal at the top reservoir and below. Also note highly repeatable signal above top reservoir despite non-repeatable VSP acquisition.

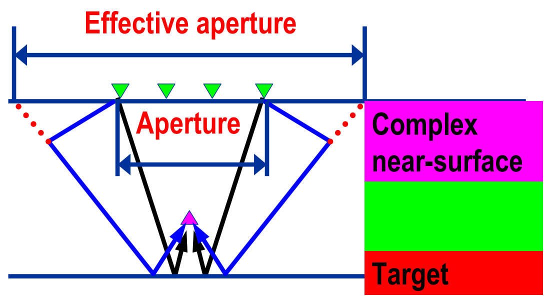

Figure 5: For any selected receiver (▲) in homogeneous media, the aperture of the source array (▼) is bounded by the ends of black rays emanating from the first and the last sources. For a heterogeneous near-surface the effective aperture is wider because scattering returns to the receiver energy that was originally emitted sideways from the source (sketched by blue arrows).

Monitoring with Virtual Sources
Figure 2 explains that VSM method should automatically correct for any changes occurring between source and receivers. Indeed time reversal with repeatedly re-acquired data automatically adjusts the focusing. The greatly improved repeatability was illustrated on a synthetic and field data (Bakulin and Calvert, 2004) and served as a justification for a Virtual Source monitoring technique using horizontal/deviated wells (Bakulin et al, 2007b). Figure 4 shows highly-repeatable time-lapse images from Peace River field (Bakulin and Calvert, 2004a, 2006) clearly showing effects of steam injection (amplitude brightening and slowdown).

More complex overburden leads to better Virtual Sources
Increasing complexity of the overburden usually deteriorates other imaging techniques. Not so with a VSM. Since measurement itself is used to redatum the data, we turn every illuminating energy into useful primary irrespective of whether it is direct arrival, reflection, multiple or diffraction. This was demonstrated by synthetic and data experiments (Bakulin and Calvert, 2006). In addition overburden complexity leads to a wider aperture of reconstructed VS aperture compared to a simpler homogenous media (Figure 5)

Virtual Shear Source
Very successful application of gating for P-waves confirmed good validity of time-reversal analogy. Further inspired by Fink's work we decided to gate around the first arrivals of shear energy and obtained Virtual Shear Checkshots and S-wave images (Bakulin and Calvert, 2005). These ideas have been successfully tested on a field data by our colleague Albena Mateeva (Mateeva et al., 2006; Bakulin et al, 2007a). Subsalt Virtual Shear Check-shot exhibited nice and clean waveforms (Figure 6) unheard of for a real data and delivered a reliable S-wave velocity profile matching shear log.

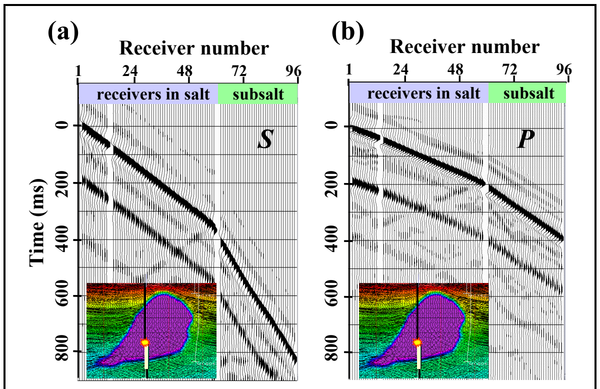

Figure 6: Common-shot gather for an S-wave (a) and a P-wave (b) Virtual Source. In both cases the Virtual Source location coincides with the top-most VSP receiver and "fires" at time zero.

Recently Bakulin and Mateeva (2008) generalized these ideas to multicomponent case. For the first time one obtained a tool to estimate *interval* shear-wave splitting below complex anisotropic overburden without actually knowing it, thus providing an alternative to restrictive and data-demanding layer-stripping technique (Winterstein and Meadows, 1991).

Wavefield separation
While gating was very successful, we always felt that better approach may be developed with proper wavefield separation. These ideas have come to fruition during the 2006 summer internship of Kurang Mehta, our current colleague. We realized that what we really desire is not only to turn each receiver into Virtual Source, but actually make the resulting data look such as if the entire overburden was replaced by a homogeneous media in order to avoid free-surface multiples and overburden reflections. In order to achieve this, cross-correlation of downgoing waves at the Virtual Source has to be performed with upgoing waves at the other receivers. In addition gating downgoing waves in first arrivals proved beneficial to remove shear waves and have a nicer P-wave radiation pattern. These ideas received excellent verification on synthetic and real data (Mehta et al., 2007) and became a new best practice for VSM. Dual-sensor summation (hydrophone + vertical geophone) was identified as a most promising approach due to phase-preserving nature, thus advocating use of 4C sensors for monitoring with VSM (Bakulin et al, 2007b,c).

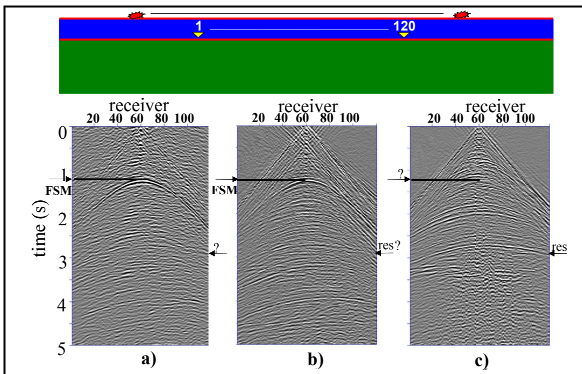

Figure 7: Demonstrating improvements caused by wavefield separation and gating on redatumed Mars OBC survey - common virtual shot gathers created by cross-correlating: (a) total wavefields at virtual source and receiver locations; (b) total wavefields but with the time-reversed wavefield gated on first arrivals; (c) downgoing waves at the virtual source location (gated on first arrivals) with the upgoing waves at the receiver.

Estimating and correcting the amplitude radiation pattern of a Virtual Source

Previous applications concentrated on correct kinematics and good repeatability. Bakulin and Calvert (2006) speculated that in principle since we measure the source signal and manufacture the VS ourselves, it should be possible to retrieve correct amplitudes. These ideas came to fruition during another summer internship of Joost van der Neut in 2007. By using spatial-frequency transforms we were able to estimate the radiation pattern of the Virtual Source and design a deconvolution process to correct it within bounds of proper illumination. True-amplitude Virtual Source gathers have been presented (van der Neut and Bakulin, 2008) for complex 1D elastic models and deconvolution approach for inhomogeneous media was outlined. In addition time-gating benefits have been quantified in terms of more homogenous radiation pattern as shown in Figure 8.

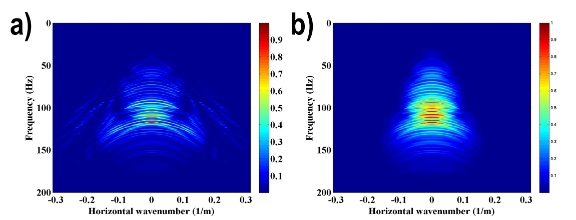

Figure 8: Amplitude radiation pattern of a Virtual Source below layred overburden generated by time reversal of : a) total wavefield, b) wavefield gated in first arrivals. Note much more homogeneous radiation pattern for gated field.

Deployment and new applications

Shell's early Virtual Source effort culminated in the creation of Reservoir Geophysics team skillfully lead by Jorge Lopez for the past three years. This group gathered a majority of Shell's Virtual Source experts and focused on developing VSM and deploying many applications. Much of the work described above has been done within this group. Look-ahead subsalt imaging with Virtual Sources became a reality (Mateeva et al., 2007). Bakulin and Calvert (2005b) speculated about Virtual Source Cross-Well and Virtual Source Cross-Spread techniques. VS Cross-Well is now a validated technique on a firm footing (Mehta et al, 2008). Virtual Source Cross-Spread uses multiple wells to create buried overlapping cross-spreads (Figure 9). Such Virtual Source Cross-Spread is already under testing in realistic 3D models with areal shot geometries (Korneev et al., 2008). Head-wave monitoring with Virtual Sources (Tatanova et al., 2007) is undergoing testing.

Conclusions

The Virtual Source Method has developed into a superb technique to image and monitor below complex overburdens. Rodney Calvert was instrumental in spearheading and bringing this technique to fruition inside Shell and within the industry as a whole. We have little doubt that progress achieved so far coupled with ongoing advances in drilling and instrumentation create a business environment where VSM applications will be routinely applied in the entire industry throughout the globe.

We greatly miss our great teacher and colleague Rodney Calvert. In our thoughts he always remains with us as a truly inspirational leader. Virtual Source Method is one of his greatest scientific heritages. He left us many others. Rodney taught to us to dream about something bigger and he lived his dream. If only one thing we can learn from him is to dream about something bigger.

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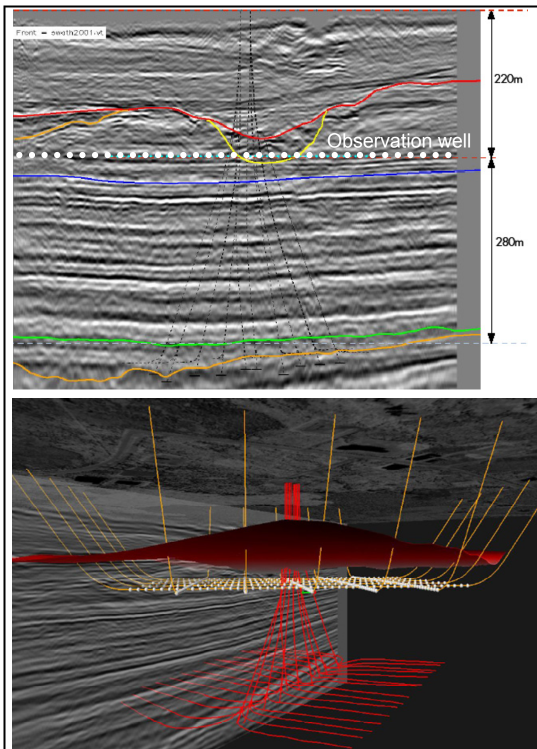

Figure 9: Conceptual design for areal field monitoring with a grid of instrumented observation wells drilled immediately below the shallow glacial channels at Peace River.

EDITED REFERENCES

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