Virtual Source: new method for imaging and 4D below complex overburden

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Summary

Complex overburden is responsible for a variety of seismic imaging/4D problems. Sometimes overburden complexity simply prevents us from imaging the deeper subsurface. We are unable to sufficiently sample and accurately build and honor near-surface velocity models.

We propose an alternative solution that does not require knowledge of the near-surface velocity model. The price to pay is placing geophones in the Earth below the most complex near-surface part while keeping sources at the surface. Receivers may sit in horizontal or slanted wells, which may be producers/injectors or dedicated sidetracks. Utilizing time reversal logic, we convert surface-to-downhole data into a new dataset with downhole Virtual Sources (VS) located at geophone positions. The resulting VS dataset with both downhole sources and receivers can be conventionally imaged requiring only the bottom portion of the velocity model below the receivers that is more simple to obtain. To illustrate the technique, we show application to one synthetic data set and one field case study.

Introduction

Near surface represents a major obstacle for seismic imaging. Ray theory is too simple to adequately describe the wave propagation. More sophisticated techniques still require detailed velocity model or some operators that can not be derived from the complex data itself.

Here we propose a new time-reversal technique for imaging VSP data that undoes all the transmission effects of the near surface and *completely eliminates* near-surface velocity model building. The new technique transforms VSP data to a new configuration with both downhole sources and receivers positioned under the near-surface. As downhole sources are simulated on a computer at the locations of borehole geophones, they are called "virtual sources" (VS) thus we name our approach "The Virtual Source method".

Physics of time reversal

To illustrate the physical principles involved, let us consider a simple experiment depicted on Figure 1a. The source excites seismic signal. Waves propagate in all directions through an inhomogeneous medium. Then a receiver array records the wavefield at each point of a closed surface surrounding the source. 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 1b). In our simple experiment the 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 (Figure 1b).

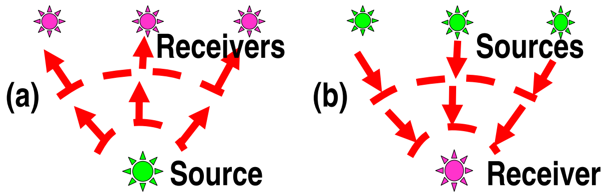

Fig. 1: Simple experiment with forward (a) and reverse (b) wave propagation explaining time reversal.

A variety of ultrasound and underwater acoustics experiments have confirmed these findings with a great deal of robustness (Fink and Prada, 2001). It also has been noticed that after the energy collapses back into the original source position the waves start to radiate again away from the original source (de Rosny and Fink, 2002). To explain this we need to recall that in the forward experiment the source brought external energy into the system that excited waves. Therefore to replay this scenario back in time, energy brought by collapsed waves should be taken out of the system at the (original) source location. Then we should observe complete rest, consistent with the original state before the source went off.

In our approach we may imagine these converging waves powering the Virtual Source that fires at the very moment when energy collapses into its location. Time reversal ensures that during collapse energy is focused at the VS point. After release of this energy in the form of outgoing waves we would observe "normal" forward wave propagation as if it was induced by a real physical source placed at the VS location. Such an approach allows us to simulate a VS at any point inside the medium by sources that are far away (Figure 2). As we directly measure the transmission responses between point of VS and each of the surface sources, we are able to focus energy back to the VS point by time reversal only and do not require the knowledge of medium velocities.

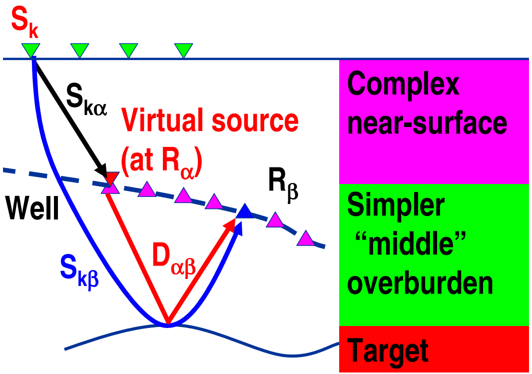

Fig. 2: Virtual Source experiment: receivers in the borehole record both downgoing wavefield through the heterogeneous near-surface (black arrow) as well as reflected signal from the deeper targets (red arrow).

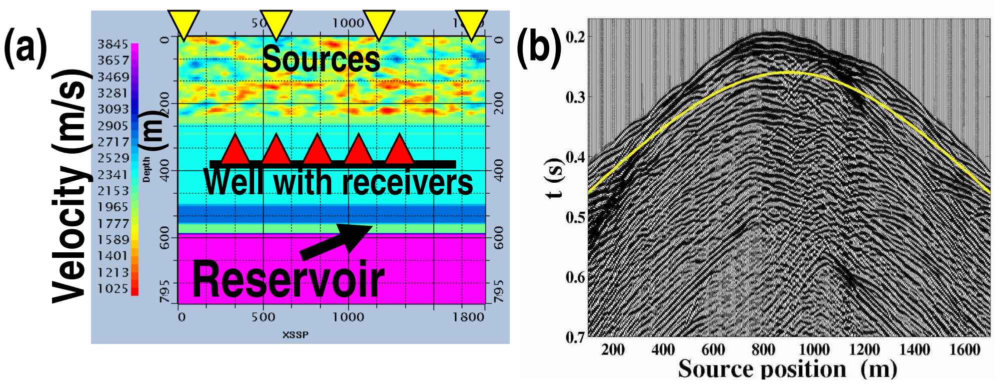

Fig. 3: (a) P-wave velocity model with extremely heterogenous near-surface (upper 250 m) used for generation of synthetic data by finite-difference method. (b) Raw receiver gather (vertical component of displacement from explosion source). Yellow line shows bottom of the time gate that went into time reversal. Experience shows that the choice of gate is not crucial.

The Virtual Source method

In our Virtual Source approach we propose acquisition geometry similar to VSP (Figure 2) with a strongly deviated or horizontal well so that the target area of the underlying deeper subsurface can be imaged. Such a well does not have to be deep as the only requirement is to have geophones below the most complex near-surface part. We also do not limit the near-surface complexity.

To remove the damaging effects of the near surface we transform the original surface-to-downhole data to a new completely downhole configuration with Virtual Sources placed at the receiver locations (Figure 2). This process consists of three conceptual steps:

- Select the downhole geophone where a VS is to be created (red triangle in Figure 2);
- Take the recorded wave fields from each surface shot to the selected Virtual Source geophone;
- Re-emit the recorded wavefield time reversed from the whole source array and record the resulting traces at each downhole receiver. This does a perfect back propagation (redatuming) undoing all static and moveout distortions.

Since our aim is to focus the energy on the image rather than in physical space [which is a must in applications like acoustic kidney stone removal (Fink and Prada, 2001)], last step is performed on the computer utilizing reciprocity and linearity. Reciprocity allows us to substitute input acquisition with surface sources and downhole receivers as an equivalent dataset to the one acquired with surface sensors and downhole excitation (note that reciprocity requires radiation patterns of sources/receivers to stay in place).

Synthetic case study

Let us examine the feasibility of the Virtual Source approach on a complex synthetic dataset resembling some features of the field trial described in next section. The upper near-surface has velocity between 900 m/s and 2900 m/s rapidly varying both in lateral and vertical directions (Figure 3a). The lower part of the model is represented by several layers with a reservoir between 562 and 590 m depth. Acquisition geometry consisted of 80 vertical geophones with 10 m spacing sitting in a horizontal well at a depth of 430 m (Figure 3a). Surface line of shots was simulated by 321 explosion sources buried at 15 m depth and spaced by 5 m.

The example gather recorded by the fixed buried receiver at $X = 900$ m is shown on Figure 3b. Despite downhole recording, the wavefield is extremely complex due to tremendous scattering happening in the near surface. It is clear, that applying only kinematic compensation in the form of static corrections would not eliminate the near-surface-caused distortions

Generation of Virtual Source data

Virtual Source data are generated according to the following algorithm. First, a location of a VS is selected at the position of any downhole receiver, say R_α (Figure 2). Then we choose receiver R_β where an output trace will be recorded. In the case of a zero-offset trace $\alpha = \beta$ and the same receiver is picked twice. Downhole seismic trace $D_{\alpha\beta}(t)$ for a selected VS-receiver pair is computed according to the simple formula:

$$D_{\alpha\beta}(t) = \sum_{k=1}^{N} S_{k\alpha}(-t) \star S_{k\beta}(t)\,, \qquad (1)$$

where $S_{k\beta}(t)$ is the trace recorded from the k-th source at the surface to the receiver R_β; $S_{k\alpha}(-t)$ is the time-reversed portion of the trace recorded from k-th source by the receiver R_β at the VS location and "$\star$" denotes convolution. Summation is carried over a certain aperture of the surface source array around location α with maximum number of elements N. Equation (1) describes nothing else but a simple time-reversal process (with an autocorrelation wavelet) as described in the previous section.

Pre-stack Virtual Shot gathers

An example pre-stack VS gather is depicted on Figure 4. The central trace corresponds to the zero offset or coinciding VS and receiver. This can be compared with the surface-to-downhole records of Figure 3b. We now start seeing coherent hyperbolic events: one with $t_0 \approx 80$ ms is the first interface below VS, while another at $t_0 \approx 140$ ms is the bottom reservoir. On top of the VS data (black) we plot another sets of seismograms (red) computed from real physical downhole sources placed at the geophone locations. Figure 4 shows that VS data (black) closely resemble the true downhole dataset (red) with all useful PP reflections clearly visible.

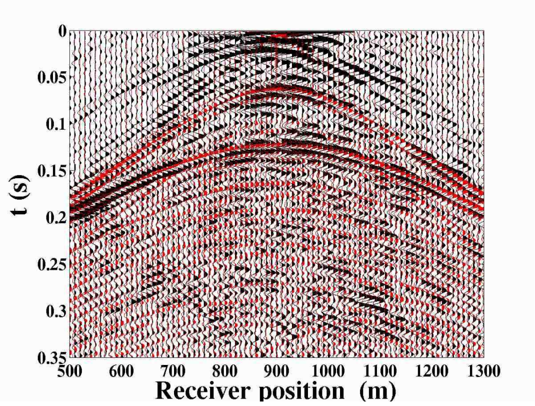

Fig. 4: VS gather (black) at $X = 900$ m overlaid by traces from real downhole source (red) at the same location.

Comparing images with surface and VS data

Let us compare images obtained using VS data with those coming from the input VSP data. Since nobody was able to construct the velocity model from the input VSP data itself, we decided to perform the comparison when *the exact* velocity model is used to image original surface-to-downhole data. This would represent a ”best possible scenario” showing the limit of conventional imaging techniques.

Figure 5 shows the comparison of PSDM (Kirchoff) images from original VSP and VS data. The two images are of similar quality, however they differ in one substantial point: the VS image was obtained *without any knowledge* of the near-surface velocity model, while the conventional image required *the exact velocity model* of the entire overburden. To obtain the VS image we only needed the lower 1-D portion of the velocity model below 430 m which is easily obtainable from the pre-stack VS data. The VS is also seen to be zero-phase and more laterally continuous.

Field case study

The Virtual Source method was applied to real 4D VSP dataset recorded in a 45° slanting well with 50 instrumented 3C geophones 8 m apart. A single shot line right above the well was used to construct 2D images. The objective is to monitor production-related changes in a shallow target below channeled overburden subject to time-varying near-surface conditions. Surface seismic, acquired in parallel, only produced a 1D velocity model after substantial static corrections which was clearly an oversimplification for a complex near surface.

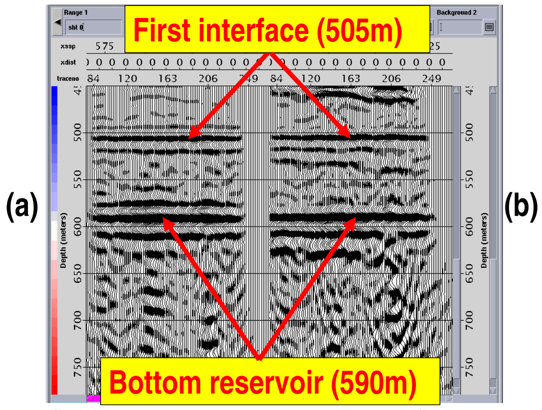

Fig. 5: PSDM images obtained with Virtual Source data (a) and original surface-to-downhole data (b). VS image (a) only needed velocity model below 430 m, whereas conventional image (b) required exact velocity model of entire overburden including the near surface.

Virtual Source data were generated from the vertical component using short hyperbolic time gate around the first arrivals that went into time reversal. This was compatible with our objective of obtaining a good quality PP image while attenuating other wave types (PS, SP etc.). Pre-stack VS dataset, consisting of 50 receivers and 50 virtual sources at identical locations, was subjected to pre-stack depth migration with a seismically-derived portion of 1D velocity model below the well. Final images for baseline and monitor surveys (Figure 6) show imperfect, yet improved repeatability above the objective level as compared to surface seismic data. Strong changes in top-reservoir reflection are clearly visible. Several intra-reservoir events of high frequency experienced substantial time delays as well as amplitude changes (Figure 6a). Surface seismic was unable to image those intra-reservoir events and in general had lower frequency content and resolution (Figure 6b).

Conclusions

The Virtual Source method allows us, in principal, to image under severely scattering overburden such as karst topography, basalt, rugged salt or other seismically challenged situations. The Virtual Source method relies on the conventional acquisition scheme of a VSP but introduces a completely new paradigm on how we treat the acquired surface-to-downhole data. We can do this simply without having to perform statics, velocity modeling, dereverberation or any modeling of the troublesome overburden. The direct measurement of transmitted wavefield through troublesome near surface is combined with time reversal in order to generate a new “virtual” dataset with both sources and receivers downhole. Time reversal is a property of wave equation in generally heterogeneous and anisotropic media. Therefore it does not rely on ray theory or any other commonly used approximations that are typically inappropriate for the near surface. As a consequence, reliable VS data may be generated even for a

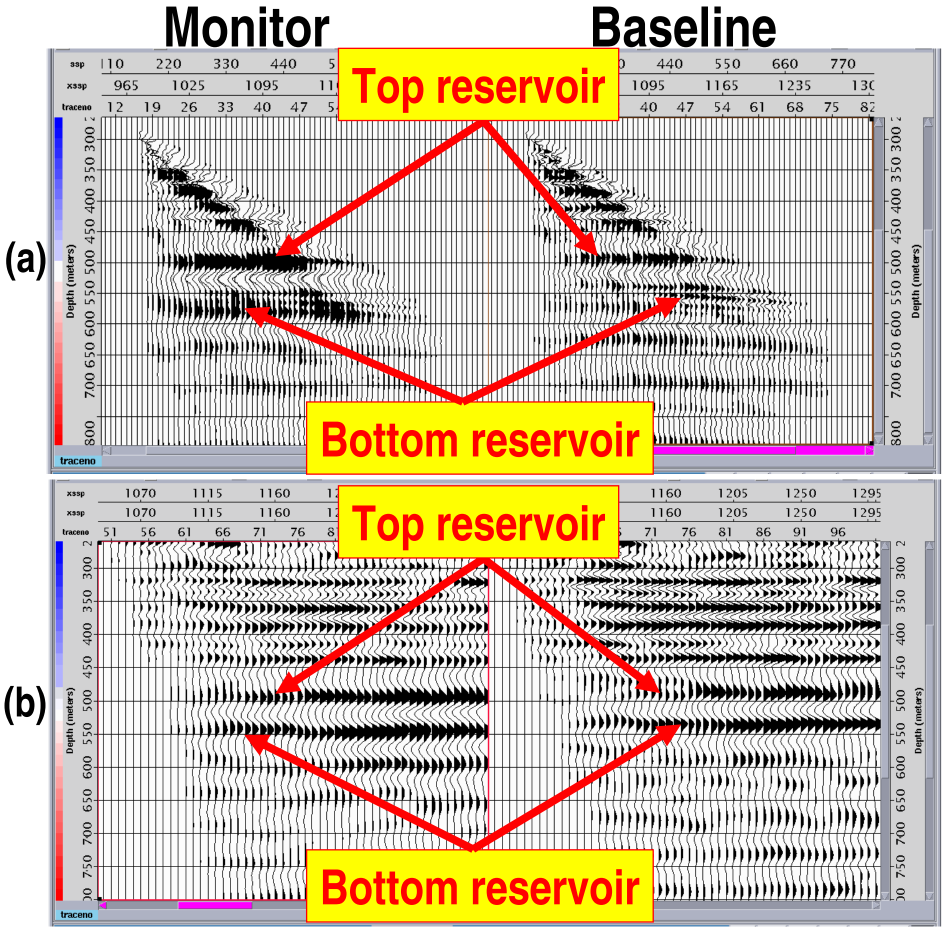

Fig. 6: (a) PSDM migrated images obtained from VS data. Seismic-derived 1-D velocity model is used but only deeper portion of it below the well is required. (b) Same portion of the Earth imaged by surface seismic 2D line (after static corrections and similar PSDM but with velocity model extending to the surface datum).

strongly heterogenous (anisotropic) near surface.

The VS method is not only able to handle a complex near surface but indeed extracts benefits from overburden complexity. Being a "full elastic wave-equation method" the VS approach collapses all the energy of the multiples, converted and diffracted waves into useful primaries. Thus what is typically considered noise in conventional imaging techniques becomes part of useful signal in the VS method.

The method is also ideal for time-lapse work using fixed receivers. The fixed geometry requirements are strictly satisfied even if the surface shot locations cannot be exactly repeated. The method also allows good repeats with different source waveforms e.g. dynamite and Vibroseis and differing near surface coupling and static conditions. As we measure a far field calibration signature for every shot into every geophone we can arrange for a desired wavelet at our Virtual Source location. All phase errors and feasible spectral differences can be removed. With the Virtual Source we have a source with a controllable radiation pattern and known zero phase signature. With multi-component receivers we can generate virtual P-wave sources with no associated shear and S-wave sources of desired azimuthal polarization with no associated P. Since the Virtual Source waveform is synthesized and does not depend upon the phase of the physical sources, the method is also an attractive way to implement the so called "day-light imaging" techniques based upon natural noise sources, particularly if the noise originates from surface scattering.

Acknowledgements

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