Virtual source redatuming applied to full-azimuth 4D buried receiver data in desert environment

Ilya Silvestrov, Andrey Bakulin, Abdullah Alramadhan, Christos Saragiotis,*
Geophysics Technology, EXPEC Advanced Research Center, Saudi Aramco

Summary
We present the first application of virtual source redatuming to full-azimuth 4D land seismic data acquired with shallow buried receivers in a desert environment with complex near-surface conditions. The processing flow is specifically designed to address issues caused by strong scattering in the near surface and to preserve time-lapse signal in the data. Comparisons with a conventional processing flow show that virtual source-based processing delivers comparable images of the subsurface with better repeatability.

Introduction
The virtual source method is a seismic redatuming technique that removes near-surface distortions and reduces seasonal variations for seismic monitoring with buried receivers (Alexandrov et al., 2015a). The method redatums surface sources without knowledge of near-surface velocities and creates a fully buried survey with virtual sources at each receiver location. In this study we apply virtual source redatuming to buried receiver data acquired using unique permanent monitoring system over a CO_2 injection pilot with complex near-surface conditions (Bakulin et al., 2016). Conventional processing without redatuming shows good repeatability between surveys with some degradation during the rainy season. In this work, we study the capabilities of virtual source redatuming to further improve repeatability and decrease the near-surface related variations.

Method
The virtual source method (Bakulin and Calvert, 2004) redatums seismic data and creates virtual shots at the position of receivers buried below the surface. This technique uses experimentally measured Green's functions between surface sources and subsurface receivers to effectively eliminate the source wavepath through the near-surface without any knowledge of the velocity model. The method involves cross-correlations inside the shot gathers and stacking of all shots to form a single trace in a virtual shot gather. The redatumed shot gather is free from near-surface distortions located above the receivers and is also more repeatable between surveys because it has been compensated for shallow seasonal variations.

Alexandrov et al. (2015a) show that repeatability of virtual source redatuming can be improved using deconvolution/reconvolution. The method involves multi-dimensional deconvolution (MDD) of the correlation function of one survey with the corresponding point-spread function (Wapenaar et al., 2010) and immediate convolution with another reference point-spread function (PSF) that is fixed for all surveys. This process corrects for different source signatures between surveys and allows to obtain more repeatable virtual shot gathers compared to a conventional cross-correlation approach. The method requires inversion of PSF matrices at each frequency and can be computationally costly. To improve efficiency, in this work we approximate the PSF matrix as a diagonal matrix and apply a single zero-offset trace deconvolution. Numerical tests show, that this approach allows to improve repeatability compared to the conventional virtual source method.

Acquisition
The seismic data were recorded using 1000 receivers permanently installed at a depth of around 70 m covering a roughly circular area (Figure 1). Receiver holes are drilled on a regular 50 by 50 m grid. Surface seismic sources, acquired on a 10 by 10 m grid, occupy a wider area shown in blue. A single vibrator is used, essentially producing point-source, point-receiver data with high fold. An example of a raw common-shot gather is shown in Figure 2. Time-lapse monitoring is done continuously with each survey acquired over a month period. Here we compare the baseline survey and two monitoring surveys acquired two and eleven months after the baseline respectively. The data is processed by two methods. The first, which we will refer to as the conventional time processing flow, is based on introducing statics and shifting the sources and receivers to the seismic reference datum using vertical timeshifts. The second approach is based on data-driven virtual source redatuming.

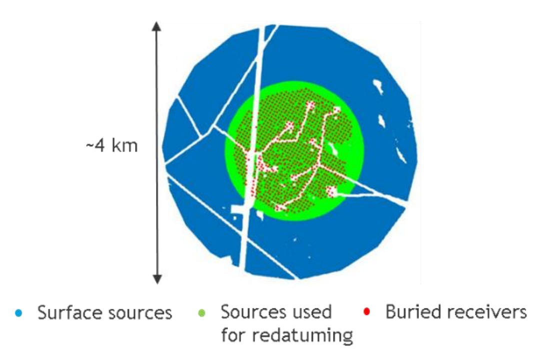

Figure 1: Acquisition geometry for 3D permanent installation with buried receivers and surface sources.

Virtual source redatuming applied to 4D buried receiver data

Theoretically, source summation in virtual source redatuming should be done over a surface enclosed around receivers. In practice, the summation is usually done over a limited aperture with actual sources. The main contribution to the virtual shot trace is coming from sources located near the stationary phase point, whereas contributions from far away shots should destructively interfere. In case of shallow buried receivers, direct waves from these far shots reach critical angles before coming to receivers and do not contribute constructively to the virtual source gather. Instead the far shots bring additional noise which deteriorates the redatumed result (Alexandrov, 2015b). To avoid this issue we sum shots only within a limited aperture around the receiver position. After testing, an optimal radius of 150 m was selected for the summation aperture. As a consequence, only shots shown by green dots in Figure 1 contribute to the redatumed image, which is significantly smaller than the actual number of sources acquired in the survey. After redatuming we obtain identical virtual source/receiver grids that are 50x50 m corresponding to a lower trace density. To take this into account, we bin the traces differently in conventional and virtual source-based flows. In the former flow, we use a bin size equal to 5 m, while in the latter case the bin size is 25 m. To fairly compare two processing flows,

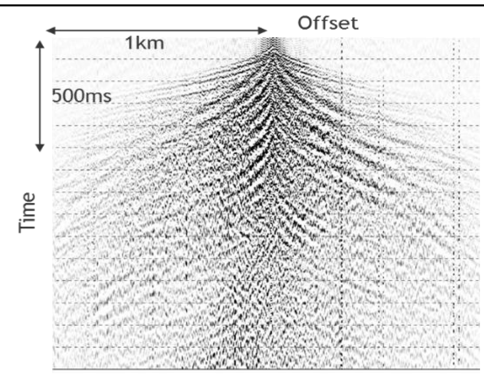

Figure 2: Example of raw 3D shot gather.

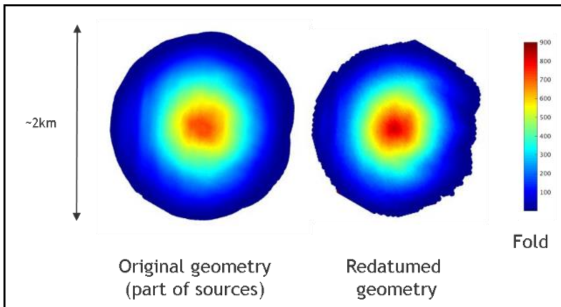

Figure 3: Fold maps for surface source – buried receiver data used in conventional processing flow after omitting extra sources (left) and buried source – buried receiver data as obtained after virtual source redatuming (right).

we use the same sources and omit from the conventional flow those ones that do not contribute to the virtual source image. Taking into account different bin sizes between the two flows, we obtain fold maps shown in Figure 3. These maps are similar suggesting that the comparison will be relevant despite differences in trace density.

Redatuming processing flow

The main steps in the processing flow based on the virtual source redatuming are shown in Figure 4.

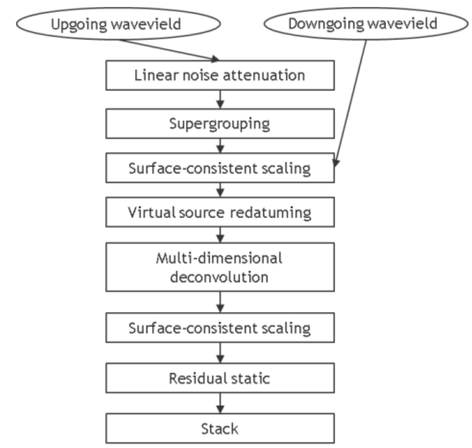

Figure 4: Processing flow based on virtual source redatuming.

Up/Down separation

At a preliminary step, the data is separated into downgoing and upgoing wavefields. In this study we did not use any up/down separation technique and instead consider the first 200 ms of the recorded data as the downgoing wavefield (Figure 4) and the rest as upgoing. The downgoing wavefield contains mostly waves propagating between sources and buried receivers in the near-surface and has a very complicated form indicating strong multiple scattering. Downgoing field is only subject to surface-consistent scaling, whereas upgoing field is heavily pre-processed to unravel reflected events and remove shear waves and linear noise.

Linear noise attenuation and supergrouping (upgoing)

In the first processing step we apply linear noise attenuation to remove strong coherent noise caused by scattering from the upgoing wavefield. Application of supegrouping (Bakulin et al., 2016b) after normal moveout correction allows us to enhance reflections and suppress unwanted events and incoherent noise.

Surface consistent scaling before redatuming

Next we perform surface-consistent scaling of both downgoing and upgoing wavefields. We follow the strategy proposed by Alexandrov et al. (2016) and estimate scalars independently for upgoing and downgoing wavefields. The analysis window for the downgoing wavefield starts from zero time and varies with offset and the approximate velocity in the near surface. The analysis window for the upgoing wavefield is based on a deeper time window. The surface-consistent scalars are obtained in a time-lapse fashion using all surveys simultaneously as explained by Alexandrov et al. (2016).

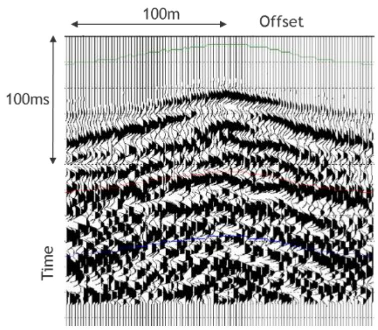

Figure 4: The downgoing wavefield shown as a 3D common-receiver gather indicating strong multiple scattering in the near-surface.

Virtual source redatuming and multidimensional deconvolution

Before virtual-source redatuming we mute the downgoing wavefield in order to reduce artifacts, essentially eliminating trailing arrivals after the first breaks, which could be multiple energy, converted waves or shallow reflections. Similar to Alexandrov et al. (2015b), we make a time-gate selection based on a trial-and-error approach. An optimal gate of 45 ms was chosen after analysis of the redatumed images in terms of repeatability and similarity to a reference stack obtained by a conventional processing flow. As discussed above, for virtual source redatuming we use only a limited number of sources lying inside an aperture of 150 m around each virtual shot position. After generating the virtual shot gathers, we apply deconvolution using diagonals of the estimated point-spread functions matrix.

Surface-consistent scaling after redatuming

Another pass of surface-consistent scaling is done after redatuming to correct amplitudes of virtual sources.

Residual statics and stack

The residual static solution is also estimated on redatumed data using 4D-compliant approach where pilot traces are used from the baseline survey. After application of statics and CDP stacking, we obtain images of the subsurface.

Images and repeatability

The stack section obtained using virtual source redatuming reveals features in common with the stack from the conventional flow (Figure 6). The redatumed image seems to have less near-surface distortions and reveal more clear details. Additional events seen on the virtual source stack are likely induced by multiples and limitations in the wavefield

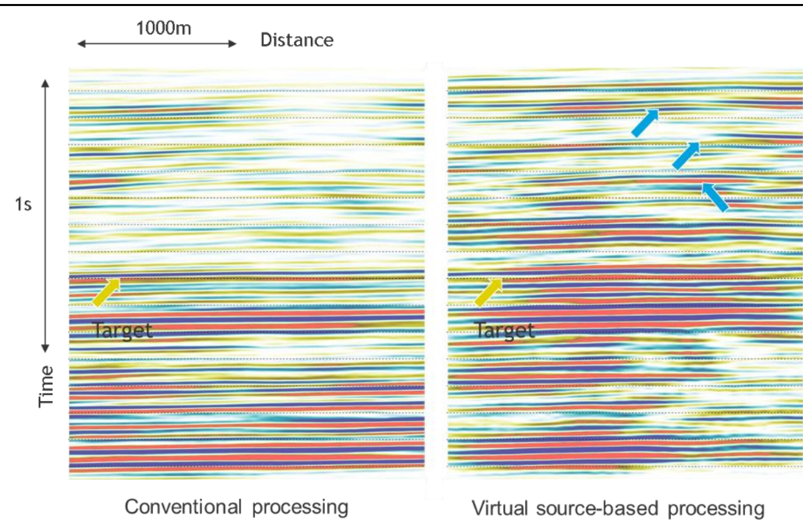

Figure 6: Stack sections after conventional flow (left) and virtual source-based processing flow (right). Yellow arrow indicates the target horizon. Blue arrows indicate some improvements in the image.

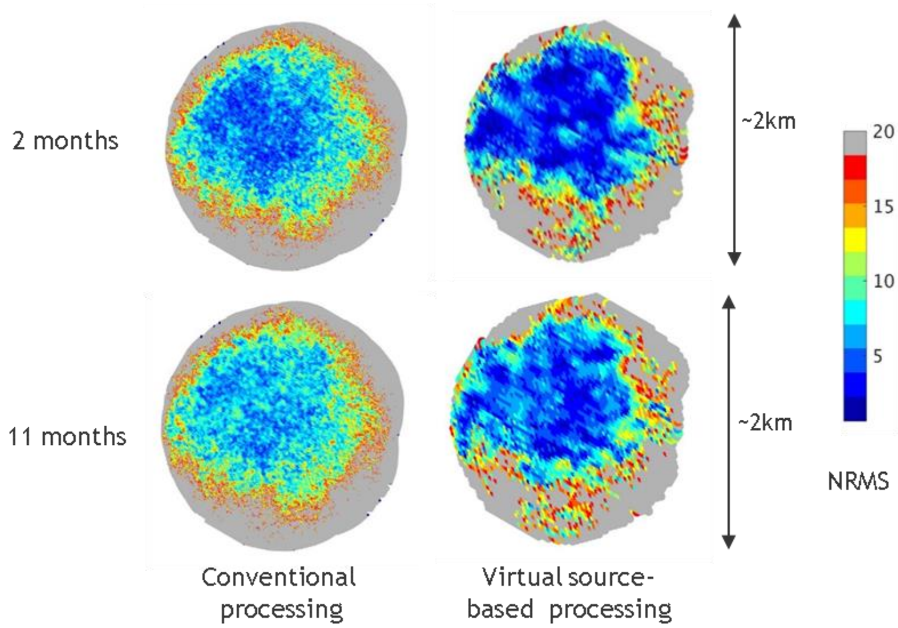

Figure 7: NRMS maps along reference horizon after two and 11 months for conventional processing (left) and virtual source images (right).

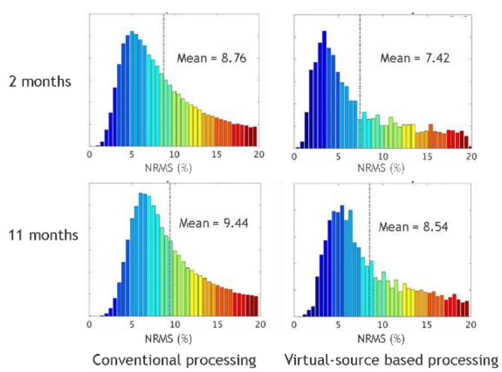

Figure 8: Histograms of NRMS values corresponding to Figure 7.

separation. To compare the repeatability of the surveys we calculate NRMS over a window along a horizon indicating by the yellow arrow (Figure 6). The maps after two and eleven months from the baseline (Figure 7) show good repeatability and do not reveal any significant variations in the subsurface.

Mean values of NRMS maps after virtual source-based processing are smaller by about 1% than after the conventional flow (Figure 8). At this low level of overall NRMS, 1% improvement is considered as significant especially when the 4D signal is small. We note that maps after virtual source redatuming become cleaner and most values are below 5% NRMS. This is expected to provide better detectability of a very weak 4D signals.

Conclusions and discussions

We present the first results of processing full-azimuth 4D land seismic data with buried receivers using the virtual source method. The processing flow is specifically designed to address issues caused by strong scattering in the near surface and to preserve 4D signal in time-lapse monitoring results. Comparison with a conventional processing flow shows that virtual source-based processing allows to get comparable images of the subsurface with better repeatability. While redatumed data has significantly lower trace density compared to the original surface source-buried receiver data, we are able to achieve comparable images and slightly better repeatability due to better removal of near-surface effects in imaging as well as seasonal and coupling variations in monitoring. All this is done automatically in a fully data-driven fashion utilizing direct downgoing arrivals at buried receivers as operators for redatuming.

Acknowledgments

We acknowledge Saudi Aramco for permission to publish this work.

EDITED REFERENCES

Note: This reference list is a copyedited version of the reference list submitted by the author. Reference lists for the 2017 SEG Technical Program Expanded Abstracts have been copyedited 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.

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