Correcting for non-repeatable source signatures in 4D seismic with buried receivers: Virtual source case study from Saudi Arabia

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Summary

Virtual source redatuming is an effective way for improving repeatability of onshore seismic data acquired with buried receivers that can suffer from near-surface variations and acquisition geometry changes. However, redatuming is less effective in correcting for amplitude variations of the downgoing wavefield caused by variable source signatures, coupling or other factors. We present an improved redatuming workflow, which has the benefits of the virtual source approach and corrects for additional non-repeatability of the downgoing wavefield between surveys. The method involves construction of the virtual source gather for each survey, deconvolution with the corresponding point spread-function (PSF) and convolving with a reference PSF. Here we employ a reference PSF computed for a homogeneous replacement near surface. This reduces imaging artifacts and provides additional control over the dominant frequency of the output data. We demonstrate a significant repeatability improvement using a field 4D multi-survey onshore dataset from Saudi Arabia.

Introduction

Time-lapse seismic reservoir monitoring on land is a challenging task. The repeatability of seismic data can suffer from various factors such as near-surface changes, variability of source/receiver geometry and coupling, and surface topography variations over time. Recently an experiment was
reported, which involved 11 repeated land seismic surveys in a desert environment over an onshore reservoir (Bakulin et al., 2012). The data were acquired using shallow buried receivers and surface sources. This acquisition design has great potential to improve repeatability as well as enable virtual source redatuming (Bakulin and Calvert, 2006; Bakulin et al., 2007) in order to address source positioning errors, source coupling changes, and diurnal/seasonal temperature variations. A synthetic case study in a realistic synthetic model (Alexandrov et al., 2012) confirmed that virtual source redatuming could reduce non-repeatability caused by the factors listed above. In particular, source-coupling variations, modeled as random phase perturbations of the source wavelet, were completely removed. All these improvements are expected if the amplitude spectra of the source signatures remain unchanged between 4D surveys. Field data has clearly showed that such an assumption is not met in desert environments of Saudi Arabia over time periods of months to years (Bakulin et al., 2014). We present an improved redatuming technique based on multi-dimensional deconvolution (MDD) that can correct for variable source amplitude spectra between surveys or more generally correct for variable downgoing wavefield illuminating in each 4D survey. The method involves construction of virtual source gathers for all surveys, deconvolving the gathers with the corresponding PSF from the same survey and re-convolving with a common reference PSF, computed assuming a homogeneous replacement layer.

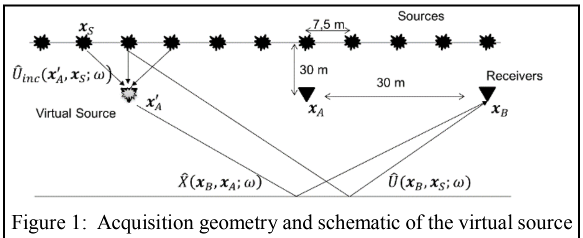

Figure 1: Acquisition geometry and schematic of the virtual source method illustrated for an actual 4D dataset from Saudi Arabia.

Theory

In order to account for source signal changes we combine two redatuming techniques: virtual source redatuming and redatuming by MDD (Wapenaar et al., 2010). Both approaches are used for retrieval of the Green's function between two receivers surrounded with sources. In the current acquisition geometry (Figure 1), surface sources can be redatumed to the receiver positions without knowledge of the velocity model. The virtual source method involves cross-correlation of the full wavefield $U(\boldsymbol{x}_B, \boldsymbol{x}_S; t)$ at the

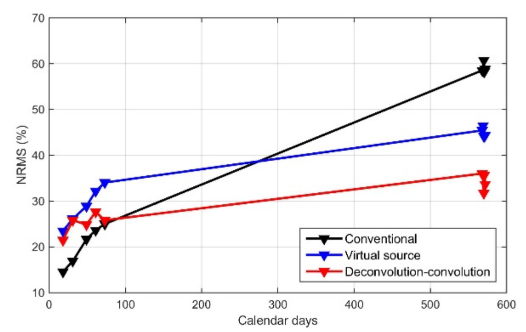

Figure 2: Stacked NRMS over reservoir window versus calendar day, computed using survey #1 as a baseline from conventional processing (black line), virtual source redatuming (blue line) and deconvolution/re–convolution approach (red line).

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receiver $\boldsymbol{x}_B$ with the incident $U_{inc}(\boldsymbol{x}'_A, \boldsymbol{x}_S; t)$ at the receiver $\boldsymbol{x}'_A$ and stacking over all sources $\boldsymbol{x}_S$:

$$\hat{C}(\boldsymbol{x}_B, \boldsymbol{x}'_A; \omega) = \sum_s \hat{U}\left(\boldsymbol{x}_B, \boldsymbol{x}_S^{(s)}; \omega\right) \hat{U}_{inc}^{*}\left(\boldsymbol{x}'_A, \boldsymbol{x}_S^{(s)}; \omega\right). \quad (1)$$

Here the caret indicates frequency domain. The correlation function $\hat{C}(\boldsymbol{x}_B, \boldsymbol{x}'_A; \omega)$ is usually interpreted as a wavefield generated by the source at the position $\boldsymbol{x}_B$ and registered by the receiver $\boldsymbol{x}'_A$. The derivation of this relation required a number of assumptions that are often violated in field experiments. In particular, the method assumes that all sources have exactly the same wavelet shape. When this assumption is not fulfilled, the radiation pattern of the virtual source will be distorted. Even though the redatumed image will be altered, as long as the source wavelets remain constant from survey to survey, the redatumed gathers will remain repeatable. Note that from equation (1) it follows that all phase spectrum variations of the wavelet will be cancelled out because the source wavelets are cross-correlated, and only changes in the amplitude spectrum will degrade repeatability of the virtual source gathers.

Another assumption is an absence of a free surface or any reflection from or above the source level. A free surface produces some reflections and creates spurious events on the redatumed gather. However as long as these artifacts remain repeatable, they again pose little direct problem to seismic monitoring.

A deeper insight into the correlation function is given by a relationship, used in MDD (Wapenaar et al., 2011):

$$\hat{C}(\boldsymbol{x}_B, \boldsymbol{x}'_A; \omega) = \int_{\partial\mathbb{D}} \hat{X}(\boldsymbol{x}_B, \boldsymbol{x}_A; \omega)\, \hat{\Gamma}(\boldsymbol{x}_A, \boldsymbol{x}'_A; \omega) d\boldsymbol{x}_A. \quad (2)$$

Here integration is performed over the receiver array on the boundary $\partial\mathbb{D}$ in the subsurface, $\hat{X}$ is the subsurface reflection response, depending solely on the properties of the medium and not on the source signature, $\hat{\Gamma}$ is the point-spread function:

$$\hat{\Gamma}(\boldsymbol{x}_A, \boldsymbol{x}'_A; \omega) = \sum_s \hat{U}_{inc}\left(\boldsymbol{x}_A, \boldsymbol{x}_S^{(s)}; \omega\right) \hat{U}_{inc}^{*}\left(\boldsymbol{x}'_A, \boldsymbol{x}_S^{(s)}; \omega\right). \quad (3)$$

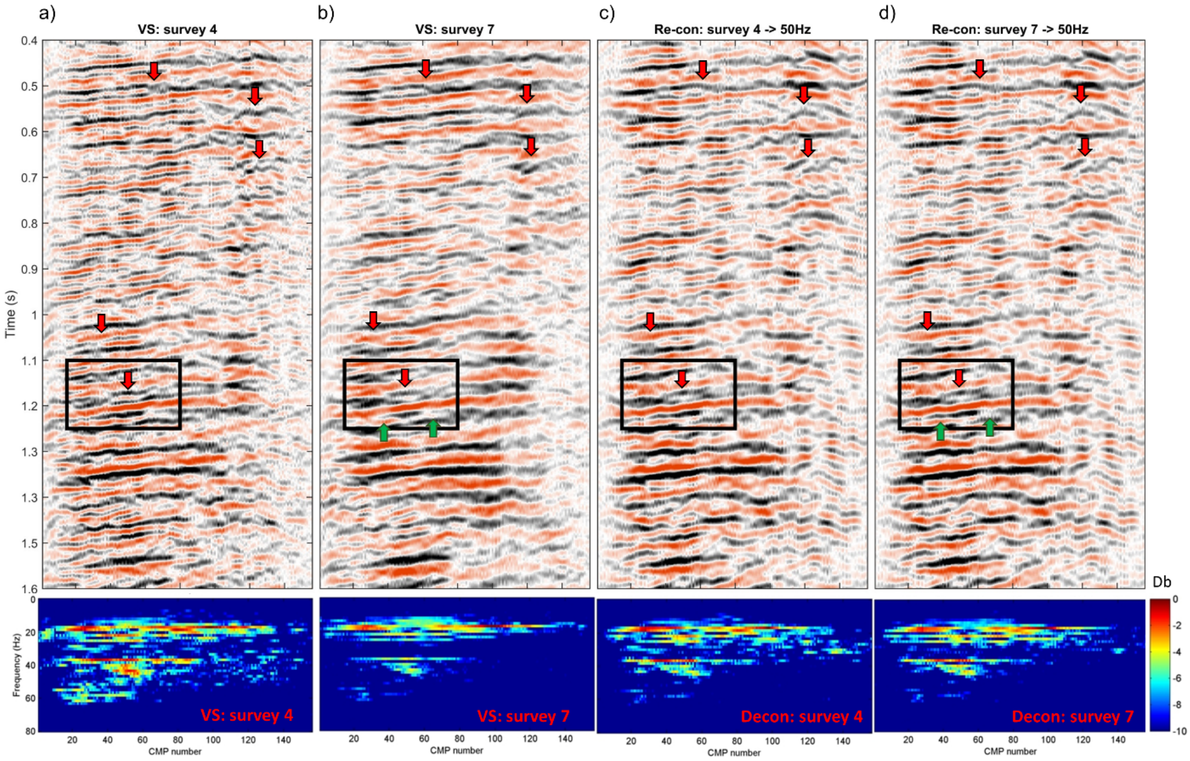

Figure 3: Stacked images and corresponding frequency spectra after virtual source redatuming of survey #4 (a) and #7 (b), as well as deconvolution/re-convolution of survey #4 (c) and #7(d). Reconvolution is done with the same homogeneous PSF. Black boxes indicate the windows used to compute average NRMS. Observe improved similarity of images and spectra after reconvolution.

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Using equation 2 we can interpret the correlation function $\hat{C}$ as the reflection response of the media $\hat{X}$ blurred by the point-spread function $\hat{\Gamma}$. Traditional MDD involves deconvolving the PSF from the correlation function. This can improve the image and remove spurious events related to the free surface as well as distortions caused by source wavelet variations especially in case of poor receiver spacing, causing spatial aliasing. However, inversion of the matrix $\hat{\Gamma}$ can easily generate undesired artefacts and deteriorate rather than improve repeatability. For this reason, we take an alternative approach that aims to improve the repeatability of virtual source data by assigning a common source wavelet to each survey, while leaving the imprint of the free-surface multiples.

Let us consider two surveys, indicated by superscripts $i = 0$ and $i = 1$, respectively. For both surveys we can compute a correlation function $\hat{C}^{(i)}$ and a PSF $\hat{\Gamma}^{(i)}$. As noticed before, the correlation function is classically interpreted as redatumed data. Alternatively, we can interpret these correlation functions as

$$\hat{C}^{(i)}(\boldsymbol{x}_B,\boldsymbol{x}'_A;\omega) = \int_{\partial\mathbb{D}} \hat{X}^{(i)}(\boldsymbol{x}_B,\boldsymbol{x}_A;\omega)\,\hat{\Gamma}^{(i)}(\boldsymbol{x}_A,\boldsymbol{x}'_A;\omega)d^2\boldsymbol{x}_A, \qquad (4)$$

where $\hat{X}^{(i)}$ is the subsurface reflection response. From this representation it is clear, that the change in the correlation function $\hat{C}^{(i)}$ describes the changes in the reflection response $\hat{X}^{(i)}$ only when the PSF $\hat{\Gamma}^{(i)}$ is repeatable. If $\hat{\Gamma}^{(1)} \neq \hat{\Gamma}^{(0)}$, theoretically we can improve the repeatability by multidimensional deconvolution, removing the point-spread function from the redatumed data. However, inversion instability can lead to additional artefacts. To overcome this issue, we convolve the retrieved reflection responses $\hat{X}^{(0)}$ and $\hat{X}^{(1)}$ with another PSF $\hat{\Gamma}^{(b)}$, where superscript b stands for "base". We can chose one of the surveys as a baseline, or use an average PSF for all surveys. Alternatively, we can construct base PSF via synthetic modeling using a simplified replacement media between source and receiver. In this study, we focus on the latter approach and generate the PSF $\hat{\Gamma}^{(b)}$ from the direct arrivals, obtained for homogeneous near-surface model between sources and receivers.

Virtual Source 4D case study from Saudi Arabia

We apply the deconvolution/re-convolution method to the 4D field data acquired over an onshore field in Saudi Arabia (Bakulin et al., 2012). The dataset we use consists of six surveys acquired during three months of the first year and five surveys collected 17 months later in a second year. The seismic data were obtained using geophones cemented at 30 m depth with 30 m inline spacing and a vertical vibrator. A carpet of sources was acquired above the receiver line (inline and crossline sampling of 7.5 m) to allow areal summation for redatuming. There were no production or other activities that could alter the properties of the reservoir, therefore minimal differences between images are expected. After conventional 4D time processing, the stacked data show poor repeatability of the target reflected arrival that reaches 60% NRMS when comparing surveys from the first and second years (Figure 2, black line). The large NRMS values are caused by a very different downgoing wavefield observed between the first and second years (Bakulin et al., 2014), that may be caused by variable source coupling (Jervis et al., 2012), near-surface changes, sand topography changes (Lisitsa et al., 2015) or combinations of the above. As a consequence, the poorly repeatable downgoing wavefield between those two years means that wavefield illuminating the reservoir has changed and this led to a poor NRMS values obtained with conventional processing (Bakulin et al., 2014). NRMS for every pair of surveys between years 1 and year 2 was above 60 % (Figure 2, black line).

Standard virtual source redatuming reduces the influence of the near surface and lowers the post-stack NRMS value to 48% (Figure 2, blue line). Figures 3a and b show a section of the virtual source gathers for surveys 4 (year 1) and 7 (year 2) and their corresponding frequency spectra. The black boxes indicate the target window used for estimating the NRMS. The NRMS between virtual source stacks for surveys #4 and #7 is still significant and reaches 49%. The spectra below the gathers show that survey 7 is missing high frequencies compared to survey 4. We improve the repeatability further by deconvolving the virtual source gathers with the corresponding PSF functions and immediately re-convolving with the reference PSF constructed for a homogeneous replacement medium. For the selected pair of surveys the deconvolution/re-convolution approach with homogeneous PSF reduces the NRMS to 36% (Figure 3c and d). Red arrows highlight some of the areas with the most noticeable improvements. Note that the frequency spectra now look very similar. When

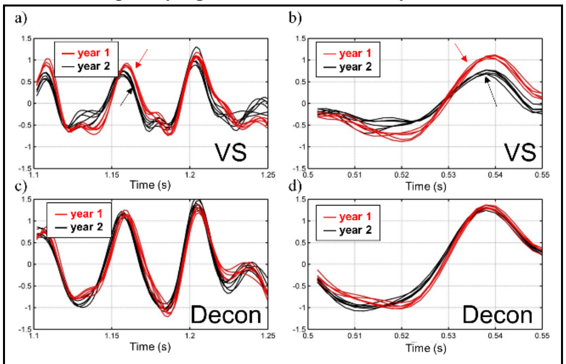

Figure 4: Traces from a single CDP location extracted from images obtained by virtual source redatuming (a,b) and deconvolution (b,c). Deconvolution uniformly improves trace similarity both for the deep target window (c) as well as shallow overburden reflector (d) compared to (a) and (b).

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computed with respect to survey 1 the NRMS never exceeds 37% (Figure 2, red line). This improvement in NRMS is approximately the same as that achieved when convolving with the PSF constructed from the baseline field data.

While we have focused on the target window, reconvolution by design improves repeatability of the entire section. Figure 4 shows stacked traces of a single CDP location overlaid from all 11 surveys from both deep and shallow time windows. Note how the traces from surveys conducted in one year, are grouped together after virtual source redatuming (red or black lines on the Figure 5a and b). Deconvolution/re-convolution systematically improves repeatability in both windows by bringing these groups closer together.

Imaging improvements

Redatuming with deconvolution/re-convolution approach also improves the image compared to the virtual source redatuming. Reflection events on the Figures 3a and b look more continuous than those on the Figures 3c and d (green arrows). In order to quantify this improvement we compute a continuity attribute we call NRMSc, which is the NRMS between neighboring traces inside the window outlined by the black box for each survey. The histogram of the NRMSc for the deconvolution/re-convolution approach is shifted to the lower NRMS values (Figure 5). This confirms that after the deconvolution/re-convolution redatuming events on the stack become more continuous than after the virtual source redatuming.

Tradeoff between repeatability and image resolution

In order to construct the synthetic PSF we need to select a wavelet along with the central frequency which was previously chosen as 50 Hz. Figure 6 shows that average NRMS (across all combinations of surveys) can be reduced by lowering the central frequency with a sweet spot around 25 Hz. This is likely a manifestation of a well-known fact that NRMS is highly correlated with the signal-to-noise ratio

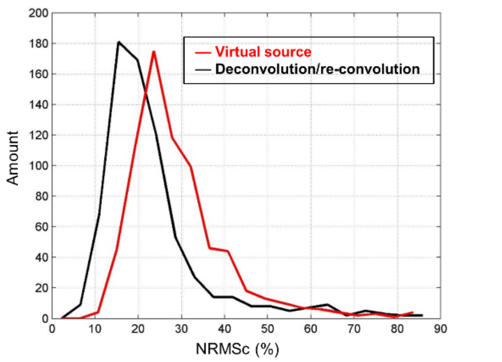

Figure 5: The image continuity attribute NRMSc computed for two redatuming approaches for surveys cunducted in year 1 and year 2.

(Pevzner et al., 2011) and that this often varies with frequency. Stacked virtual source data has highest energy around 20 to 25 Hz, implying that this part of the data is the most repeatable, whereas lower and higher frequencies with smaller amplitudes have a reduced signal-to-noise ratio and as a consequence are less repeatable. We cannot simply select the best central frequency based on repeatability alone as it would compromise the vertical resolution of the images. As such the final frequency selection for reconvolution needs to be chosen based on the desired optimal combination between repeatability and image quality which in our case seems to be achieved between 35 and 45 Hz.

Conclusion

We described an improved redatuming technique that corrects for variable source signatures between 4D surveys acquired with buried receivers. The method involves deconvolving the virtual source gather of each survey with the corresponding PSF from the same survey and re-convolving with another reference PSF. Here, we have modeled the reference PSF in a homogeneous replacement media between sources and receivers. We demonstrated the feasibility of this technique using 4D field data from Saudi Arabia where it significantly reduced maximal NRMS from about 60% to about 35%. We also observe that the deconvolution/re-convolution approach improved the continuity of target events on the stack compared to conventional virtual source redatuming. Using a synthetic PSF based on a homogeneous replacement media provides an additional parameter to tweak for better repeatability – the dominant frequency of the signal. This parameter should be chosen so that it provides an optimal combination of repeatability and vertical resolution of the final image.

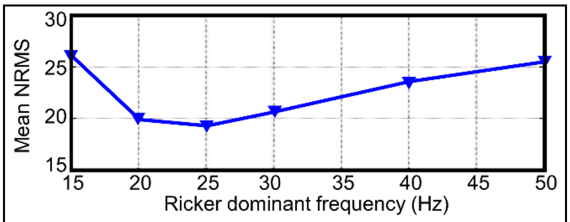

Figure 6: Average NRMS across all combinations of surveys (years 1 and 2) versus dominant frequency of the Ricker wavelet used for computing reference PSF for the re-convoltuion step.

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