MADRID 2015
1-4 June 2015 | IFEMA Madrid

Tu N101 15

Improving Repeatability of Land Seismic Data Using Virtual Source Approach Based on Multidimensional Deconvolution

D. Alexandrov* (Saint Petersburg State University), J. van der Neut (Delft University of Technology), A. Bakulin (Saudi Aramco, EXPEC ARC) & B. Kashtan (Saint Petersburg State University)

SUMMARY

We present a new redatuming workflow developed for improving the repeatability of seismic data and designed specifically to account for changes in the source signatures or variations in downgoing fields in general. The new approach is based on the virtual source method with the same potential for reducing non-repeatability, associated with acquisition geometry changes and variations in the near surface. To correct for changes in the source wavelet between surveys, we suggest deconvolving the virtual source gather of the monitor survey with the point-spread function (PSF) of the same survey, and immediately convolving with the PSF of the base or reference survey. The PSF governs the radiation pattern of the virtual source. Trying to completely deconvolve the effects of individual PSFs on each virtual source response may degrade repeatability due to possible amplification of noise. Instead, we try to equalize radiation patterns of the virtual sources across all repeat surveys by reassigning a new reference PSF to all surveys. We apply the deconvolution-convolution method to a field 4D dataset with buried receivers and demonstrate significant improvement in repeatability.

Introduction

Time-lapse seismic monitoring is increasingly being used for optimizing field production. This monitoring is particularly challenging on land where image quality is reduced and repeatability is an issue. Using buried sources and receivers (Schisselé and Forgues, 2009) is one way to guarantee fixed acquisition geometry and coupling, and reduce the influence of near-surface changes on the data repeatability. In cases where a significant fold is required for imaging, burial of a large number of sources can be inefficient and costly. Recently, an experiment was conducted in a challenging desert environment with surface sources and shallow buried receivers (Bakulin et al., 2012). Using downhole sensors allowed removing a significant amount of receiver-side 4D noise. Source positioning errors, source coupling variations, and diurnal/seasonal temperature variations degraded the repeatability of the seismic data. These issues can be addressed to some extent by redatuming of the surface source to the buried receiver location with the virtual source method (Bakulin and Calvert, 2006; Bakulin et al., 2007). Alexandrov et al. (2012b) showed how virtual source redatuming by cross-correlation could improve repeatability on synthetic examples, using a realistic horizontally layered elastic model with shallow buried receivers. In particular, they modeled variations of the source coupling as random phase perturbations of the source signal, while the amplitude spectra remained unchanged. Variations of the source amplitude spectra affect the radiation pattern of the virtual sources, making redatuming less effective in improving the repeatability. In this work, we present a new redatuming workflow — based on multidimensional deconvolution (MDD) — that can effectively remove differences in source signature between surveys and correct the virtual source radiation conditions. We demonstrate improved repeatability using 4D field data from Saudi Arabia.

Multidimensional deconvolution and convolution

Virtual source redatuming and interferometry by MDD are two redatuming techniques based on the reciprocity theorems of correlation and convolution type respectively (Wapenaar et al., 2010). Both approaches allow redatuming of the sources to the receiver locations without knowledge of the intervening velocity model and obtaining the reflection response as if the media above the receivers is homogeneous (Figure 1). Traditionally, virtual source redatuming is performed by cross-correlating the full wavefield $U(\boldsymbol{x}_B, \boldsymbol{x}_S; t)$ with the incident wavefield $U_{inc}(\boldsymbol{x}'_A, \boldsymbol{x}_S; t)$ and stacking over all sources:

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

Here the caret indicates the frequency domain, $\boldsymbol{x}_S$ is the source coordinate, $\boldsymbol{x}_B$ and $\boldsymbol{x}'_A$ – receiver coordinates. The resulting correlation function $\hat{C}(\boldsymbol{x}_B, \boldsymbol{x}'_A; \omega)$ describes the wavefield that is generated by the source at the location $\boldsymbol{x}_B$ and recorded by the receiver $\boldsymbol{x}'_A$. A number of assumptions made for this method often cannot be fulfilled in field conditions. In particular, the method assumes that all sources emit exactly the same wavelet.

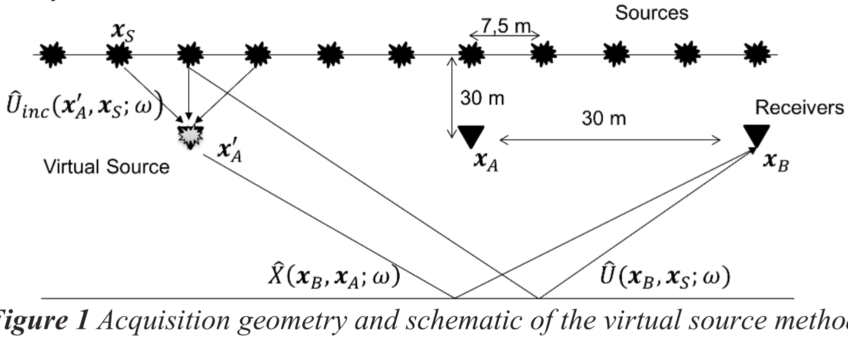

***Figure 1** Acquisition geometry and schematic of the virtual source method.*

A deeper insight into the correlation function composition gives a relationship that can be used in MDD (Wapenaar et al., 2011):

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

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

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

From equation 2 we can conclude that correlation function is the reflection response of the media filtered by the point-spread function $\hat{\Gamma}$. Therefore, the reflection response can be reconstructed using multidimensional deconvolution of the correlation function with the point-spread function. This can be beneficial, for instance, when we want to improve the image and remove spurious events and artifacts related to the free-surface multiples. Rigorous inversion of the matrix $\hat{\Gamma}$ can easily generate undesired artifacts and deteriorate rather than improve the repeatability. For this reason, we take an alternative solution, still having the potential to improve the repeatability of virtual source data, without aiming to eliminate the source signature and free-surface multiples.
Consider a base and a monitory survey, indicated by subscripts $i = 0$ and $i = 1$, respectively. For both surveys, we can construct a correlation function $\hat{C}^{(i)}$ as in equation 1 and a point-spread function $\hat{\Gamma}^{(i)}$ as in equation 3. As noted earlier, the correlation function is classically interpreted as redatumed data. Alternatively, we can interpret these correlation functions as

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

where $\hat{X}^{(i)}$ is the subsurface reflection response. From this representation, we learn that the change in the correlation function $\hat{C}^{(1)} - \hat{C}^{(0)}$ is a solid measure for the change in the reflection response $\hat{X}^{(1)} - \hat{X}^{(0)}$ if and only if the point-spread function is repeatable, such that $\hat{\Gamma}^{(1)} = \hat{\Gamma}^{(0)}$. If $\hat{\Gamma}^{(1)} \neq \hat{\Gamma}^{(0)}$, the repeatability can theoretically be improved by incident-field deconvolution, i.e., rigorously removing the point-spread function from the redatumed data. Since this inversion is not always stable, additional artefacts can be generated with such an approach. To overcome this problem, we suggest convolving the retrieved responses $\hat{X}^{(0)}$ and $\hat{X}^{(1)}$ with the point-spread function of the base or reference survey $\hat{\Gamma}^{(0)}$, according to

$$\hat{C}^{(i0)}(\boldsymbol{x}_B, \boldsymbol{x}'_A; \omega) = \int_{\partial\mathbb{D}} \hat{X}^{(i)}(\boldsymbol{x}_B, \boldsymbol{x}_A; \omega)\, \hat{\Gamma}^{(0)}(\boldsymbol{x}_A, \boldsymbol{x}'_A; \omega) d^2\boldsymbol{x}_A. \tag{5}$$

Here, $\hat{C}^{(i0)}$ is the corrected correlation function of survey i.
We refer to this operation as deconvolution-convolution (or reconvolution), since the original point-spread function is removed and thereafter replaced by its equivalent from the base or reference survey. Since the temporal and spatial bandwidth of $\hat{\Gamma}^{(1)}$ and $\hat{\Gamma}^{(0)}$ are comparable, instabilities in the deconvolution step are effectively suppressed in the convolution step.

Field data example

We apply the deconvolution-convolution method to the field data from Saudi Arabia (Bakulin et al., 2012). The seismic data were acquired with a single surface vibrator sweeping every 7.5 m and recorded by receivers buried at 30 m depth with 30 m inline spacing (Figure 1). We use the data from six surveys recorded during first year and five surveys in the second year. After careful time domain pre-processing, the data was redatumed with the virtual source method and stacked to produce basic images. We compute NRMS between stacks in a 150 ms window centered around the target reflection to quantify the repeatability. Since the reservoir in this case experienced no production or injection during the surveys, we expect minimal differences between images. When we compare surveys performed within one year, NRMS does not exceed 20%. In contrast, we observe a significant increase of NRMS values up to 60% when comparing between first and second year (Bakulin et al., 2014). Close study of the pre-stack data reveals significant differences between early mostly downgoing arrivals from surveys 4 and survey 7 performed seventeen months apart (see Figure 2b). The differences between the surveys 7 and 11, which are six days apart, are hardly visible (Figure 2a). Note that representative gathers on Figure 2 are obtained with a single shallow buried sensor at 30m depth. The maximum offset on these seismograms is only 75m. Therefore, they do not contain surface modes and show mainly body waves, which propagate downwards and eventually illuminate our deep reservoir at 2 km depth. These variations in downgoing illuminating fields lead to different reflected arrivals that are additionally affected by poorly-repeatable noise such as surface waves. Indeed early arrivals on the Figure 2a and 2b have average NRMS of 20% and 50% respectively, whereas deep pre-stack reflections (after noise removal) have NRMS of 140% suggesting that they are completely unrepeatable. While there is only so much we can do to enhance noise removal, we can correct the reflection data for variable illumination using a wave-equation approach. This should make complex reflection responses much more similar between time-lapse surveys and improve repeatability. To achieve that, we use stable (repeatable) parts of the downgoing wavefield presented on the Figure 2 to construct the point-spread functions $\hat{\Gamma}$ according to equation 3 and perform deconvolution-convolution after virtual source redatuming.

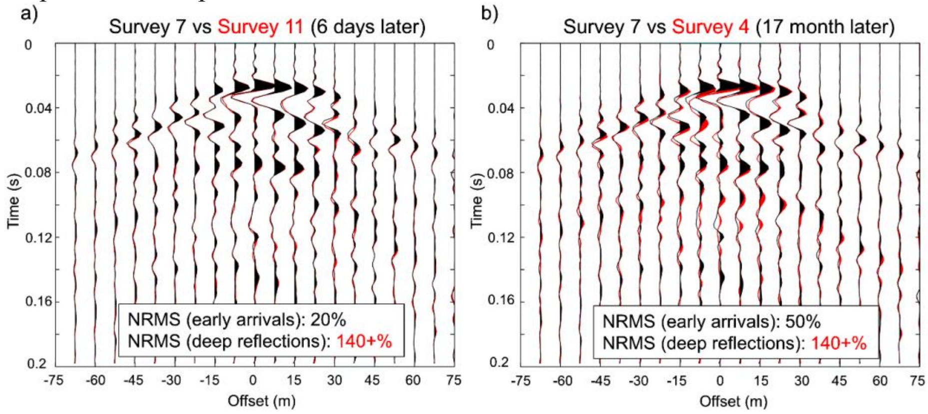

Figure 2 *Overlay of common-receiver gathers for 30-m geophone from surveys a) 7 (black) and 11 (red) spaced by six days and b) surveys 7 (black) and 4 (red) separated by 17 months.*

Figure 3 shows three virtual source (VS) stacks and corresponding spectra for the VS gathers. The black boxes indicate the window used for estimating of the NRMS between images. The NRMS between VS stacks for the surveys 4 and 7 reaches 49%. The spectra below the image show that survey 7 is missing high frequencies compared to the survey 4. Deconvolution-convolution gives a significant improvement in repeatability, decreasing NRMS to 37% and correcting the frequency spectrum in the area highlighted with the red ellipse (Figure 3c).

We repeat these tests for all surveys and choose survey 7 as a reference survey. After deconvolution $\hat{C}^{(i)}$ with $\hat{\Gamma}^{(i)}$ we convolve the result with $\hat{\Gamma}^{(7)}$. Comparing surveys between first and second year (surveys 1–6 vs 7-11) deconvolution-convolution improves the repeatability by 3–12% compared to the regular VS redatuming and by impressive 15–20% compared to the conventional stack.

Conclusions

We presented an improved VS redatuming method developed to enhance seismic data repeatability. By deconvolving correlation function of each survey with the corresponded PSF and convolving immediately with the PSF of the reference survey, we correct differences in radiation patterns of the virtual sources. This strategy avoids undesired artefacts from deconvolution that can deteriorate virtual source repeatability, while still effectively aligning the source functions of the base and monitor surveys. The reference PSF can be computed from one of the surveys or estimated from modeling in an ideal simplified replacement media. We demonstrated the feasibility of the new technique on the field data where it reduced NRMS from 56-58% for conventional stack without redatuming to 35–40% on VS stacks. Choosing a PSF with a lower centroid frequency as a reference produced the best results. We expect further improvements after up-down wavefield separation and using decomposed wavefields in the VS redatuming and deconvolution-convolution steps.

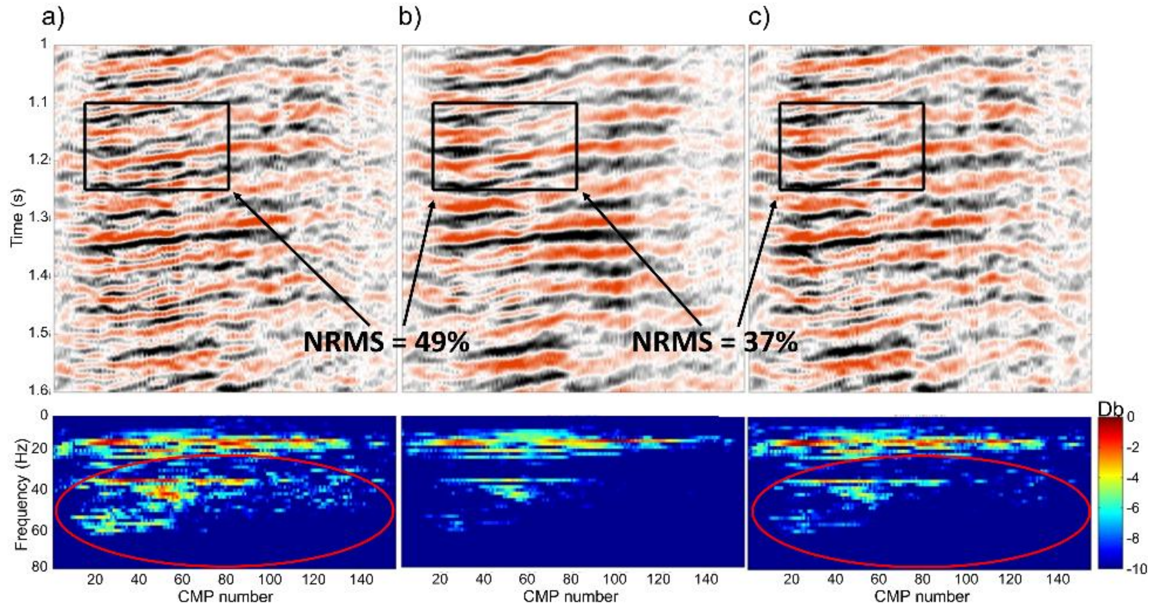

Figure 3 *Stacked gathers and corresponding frequency spectra after: a) VS redatuming of the survey 4, b) VS redatuming of the survey 7, and c) deconvolution-convolution of the survey 4, using survey 7 as a reference. Black boxes indicate the windows used to compute the average NRMS.*

Acknowledgements

We thank Saudi Aramco for allowing publishing this work and financial support via CRDF grant RUE1-ST-30031-ST12. We thank Abdullah Ramadan and Christos Saragiotis (both Saudi Aramco) for support of this study. The authors additionally acknowledge Saint Petersburg State University for a research grant 11.38.217.2014.

References

Alexandrov, D., Bakulin, A., and Burnstad, R. [2012a] Redatuming of Synthetic Land Data with Shallow Buried Receivers Using the Virtual Source Method. *82nd Annual SEG meeting*, Expanded Abstracts, 1–5.

Alexandrov, D., Bakulin, A., Burnstad, R., and Kashtan, B. [2012b] Improving land seismic repeatability with virtual source redatuming: synthetic case study. *82nd Annual SEG meeting*, Expanded Abstracts, 1–5.

Bakulin, A. and Calvert, R. [2006] The virtual source method: Theory and case study. *Geophysics*, **71**, SI139–SI150.

Bakulin, A., Mateeva, A., Mehta, K., Jorgensen, P., Ferrandis, J., Sinha Herhold, I., and Lopez, J. [2007] Virtual source applications to imaging and reservoir monitoring. *The Leading Edge*, **26**, 732–740.

Bakulin, A., Jervis, M., Burnstad, R., Kelamis, P. [2012] The feasibility of permanent land seismic monitoring with buried geophones and hydrophones in a desert environment. *74th EAGE Conference and Exhibition*, Extended Abstracts, 4–7.

Bakulin, A., Smith, R., Jervis, M., and Burnstad, R. [2014], Near-surface changes and 4D seismic repeatability in desert environment: From days to years. 84th *Annual SEG meeting*, Expanded Abstracts, 4843-4847.

Schisselé, E., Forgues, E. [2009] Seismic Repeatability–Is There a Limit? *70th EAGE Conference and Exhibition*, Extended Abstracts, 8–11.

Wapenaar, K. and Van der Neut, J. [2010] A representation for Green's function retrieval by multi-dimensional deconvolution. *Journal of the Acoustical Society of America*, **128**(6), EL366–EL371

Wapenaar, K. and Van der Neut, J. [2011] Seismic interferometry by crosscorrelation and by multidimensional deconvolution: a systematic comparison. *Geophysical Journal International*, **185**, 1335–1364.