# Handling source and receiver scalars in land seismic data for Virtual Source applications to imaging and reservoir monitoring

*Dmitry Alexandrov, Saint Petersburg State University; Andrey Bakulin*, Abdullah Ramadan, Geophysics Technology, EXPEC Advanced Research Center, Saudi Aramco*


## Summary

We perform synthetic tests to evaluate how source and receiver amplitude variations can affect image quality and repeatability of the virtual source gather. We use different workflows in order to either remove the effect of these variations after redatuming or correct them before redatuming. In particular, we consider a multi-dimensional deconvolution-convolution redatuming approach and use it to improve imaging and repeatability in the presence of source amplitude variations. In addition, we demonstrate how surface-consistent scaling can balance the amplitudes of both sources and receivers. We demonstrate that the surface-consistent processing using a deeper reflection time window produces the best result. However, a shallow time window that includes early arrivals can still be used when reflection amplitudes are not reliable.


## Introduction

Virtual source redatuming (Bakulin and Calvert, 2004) is a powerful technique that can address various imaging and monitoring challenges (Bakulin et al., 2007). However, many of the assumptions behind the method are not satisfied in practice, especially for land data. This does not invalidate the technique, but rather requires specialized pre-processing that condition the data in a way that gives the best chance for redatuming to work. In this study, we specifically focus on the effects of source and receiver scaling. We emphasize that virtual source can handle natural or physics-based amplitude variations associated with the excitation or wave propagation without any additional corrections. However, it cannot address other amplitude variations caused by practical issues such as variable source coupling and reduction in vibrator strength near various field obstructions such as wells, pipelines, buildings, roads etc. First, we demonstrate that source variations can cause significant redatuming artefacts to pre-stack virtual source gathers and therefore need to be corrected. Since the virtual source method is often used for monitoring with buried receivers, it is important to design those corrective measures in such a way not only we eliminate imaging artifacts, but we also maintain or improve repeatability between repeated surveys. We outline possible ways to perform source and receiver scaling corrections for two modifications of virtual source imaging used in practice: basic cross-correlation based redatuming and a more advanced approach involving multi-dimensional deconvolution. The latter approach was designed to both correct for variable source signatures between surveys and improve repeatability (Alexandrov et al., 2015). While multi-dimensional deconvolution does help to correct for different wavelet shapes between repeated surveys, we show that it is unable to deal with other source scaling issues and as a consequence may also suffer from similar imaging artifacts.

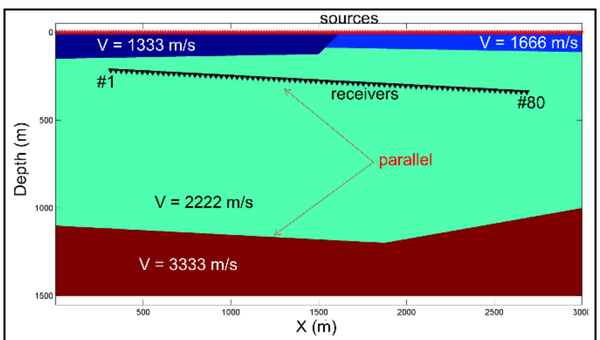

Figure 1: Acoustic model and acquisition geometry

## Synthetic case study of imaging and monitoring

We illustrate the concept using a time-lapse 2D dataset acquired with buried receivers (Figure 1) inspired by a field test (Bakulin et al., 2012). We focus on the quality of redatumed images as well as their repeatability when shots and receivers are subject to arbitrary and time-dependent scaling. A single reflector is located at depth of around 1100 m, whereas the near surface comprises two low velocity zones with V = 1333 m/s in the left part of the model and V = 1666 m/s in the right part (Figure 1). A dipping receiver line with a 30 m spacing at a depth range 216 to 340 m, was

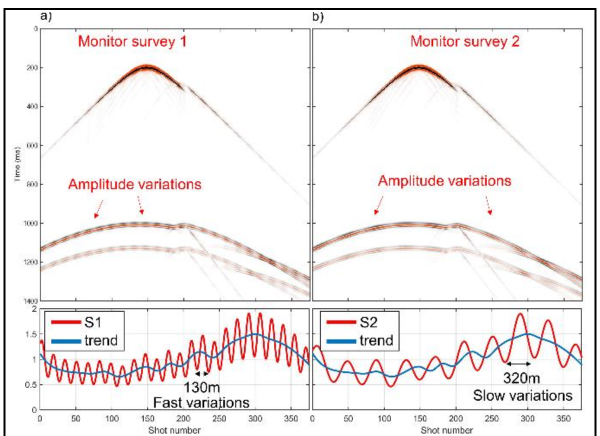

Figure 2: Common-receiver gathers of the a) monitor survey 1 and b) monitor survey 2 with their corresponding scalars S1 and S2.

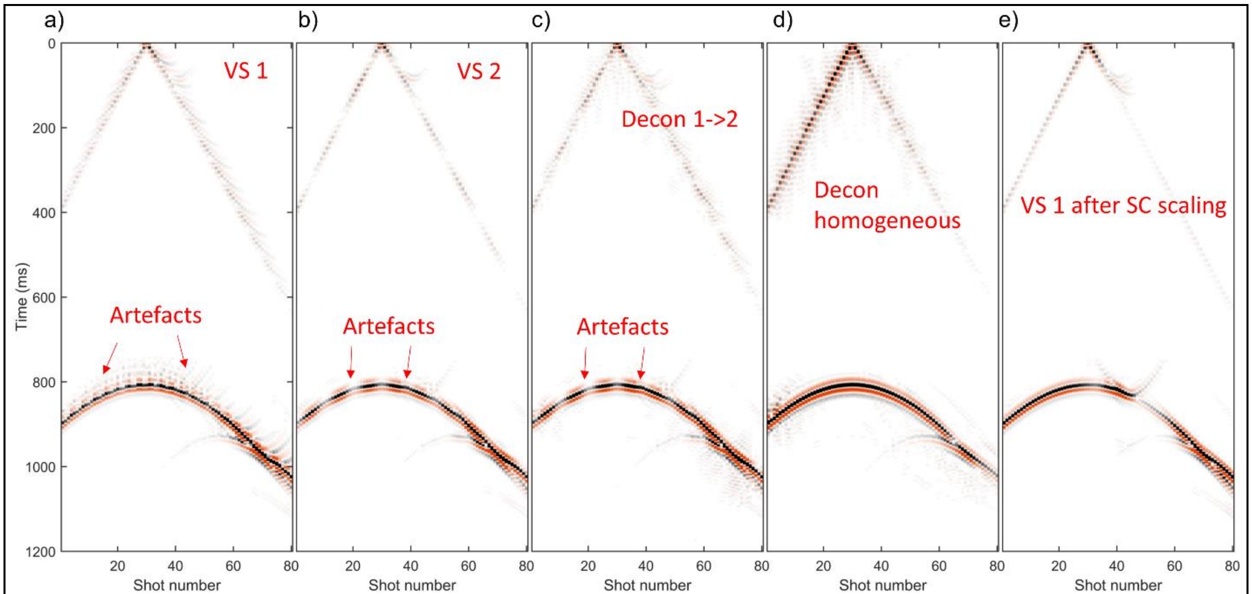


Figure 3: Common receiver gathers after redatuming using different approaches: virtual source redatuming of the a) survey 1, b) survey 2, c) deconolution-convolution of survey 2 data using survey 1 as a reference, d) deconvolution-convolution of survey 1 or survey 2 using homogeneous PSF, and e) virtual source redatuming of the survey 1 after SC scaling using a shallow window.

parallel to one of the reflecting interfaces. There were 376 surface shots at a spacing of 8 m. For simplicity we did not introduce a free surface in the model. We first analyze the effect of shot scalars only and then consider the general case when both sources and receivers are scaled. Since each variant of VS redatuming has different requirements, we analyze pre-processing requirements for all three scenarios and then summarize the results in a table.

**Source amplitude variations**

In this test we alter source amplitudes in two ways, while keeping the receivers unscaled. Figure 2 shows common receiver gathers after scaling along with corresponding amplitude scalars. The seismogram contains three events: the direct wave, the reflection from an interface at 1000 m and the receiver ghost arrival from the near-surface interface. To generate the monitor surveys we applied oscillating shot scalars with high (S1) and low (S2) spatial frequencies that had a wavelength of 130 m and 320 m respectively. The blue line (Figure 2) indicates a common trend of selected scalars. These oscillations can be observed on the reflection and ghost arrivals as ripples.

After the virtual source redatuming, amplitude variations transform into the artefacts visible on the common receiver gathers. The fast source amplitude oscillations distort traces of the virtual source gather and add noise before the reflection event (Figure 3a). Slower source amplitude variations introduces more subtle artefacts that look like amplitude variations in the reflection (Figure 3b). The average NRMS between two monitor surveys after redatuming computed in the window over the reflection is 48%.

**Multidimensional deconvolution-convolution**

One way to improve repeatability during the redatuming process is to use a deconvolution-convolution approach (Alexandrov et al., 2015). This method involves multi-dimensional deconvolution of the correlation function of one survey with the corresponded point-spread function

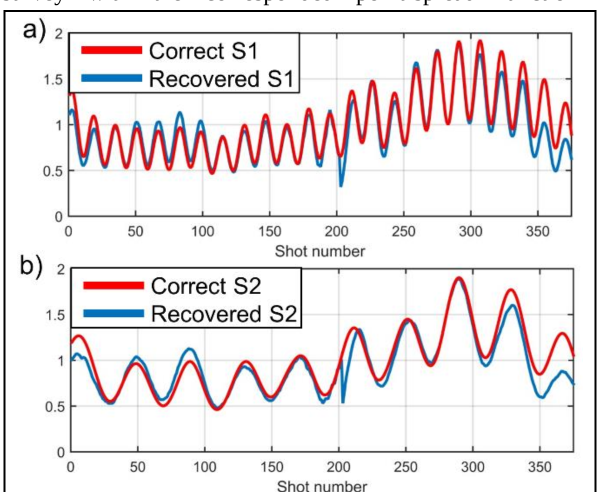


Figure 4: Shot scalars estimated using SC scaling with a deep time window for the a) monitor survey 1 and b) monitor survey 2.

(Wapenaar et al., 2010) and immediate convolution with the point-spread function (PSF) of another survey. This way we correct different source signatures of the surveys and obtain repeatable virtual source gathers. Figure 3c shows the result of the deconvolution-convolution approach applied to the monitor survey 1 using survey 2 as a reference. The NRMS between reflections on the seismograms 3b and 3c is reduced to an average of 9%. However, with this workflow we do not remove the artifacts, but rather replace artifacts of the redatumed survey 1 with the artefacts of the survey 2. In order to suppress artifacts we can apply the deconvolution-convolution method to both surveys using a PSF, computed in a homogeneous media. The resulting gathers show good repeatability with average NRMS of 6% as well as continuous reflection event without artifacts (Figure 3d).

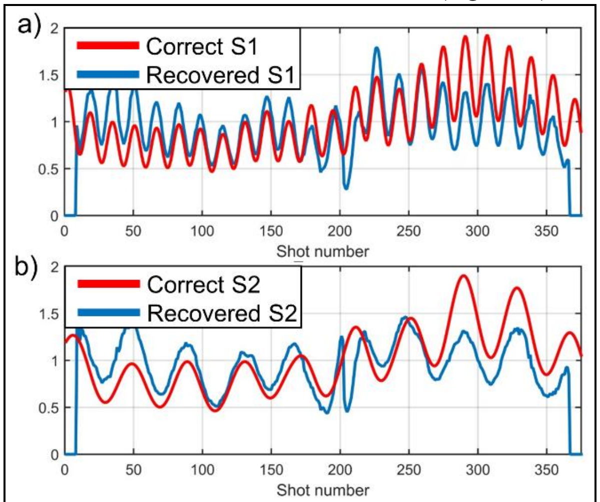


Figure 5: Shot scalars estimated using SC scaling with a shallow time window for the a) monitor survey 1 and b) monitor survey 2.

**Surface consistent scaling**

Alternatively we can correct the source amplitudes using surface consistent (SC) scaling separately to each gather before redatuming (Almutlaq and Margrave, 2013). We perform SC scaling using 2 terms: source and receiver, and then apply only shot scalars. Traditionally, a window is selected over reflections where the algorithm will try to match the wavefields. However, reflection arrivals are often obscured with surface waves or unsuppressed noise. In these situations, using early arrivals with higher signal-to-noise ratio can be more preferable.

We use two different windows for SC scaling:

1) 800 – 1700 ms over all offsets
2) 0 – 700 ms over offsets 0 – 250 m.

The second window includes only early arrivals, while the first includes reflection only. Figures 4a and 4b show scalars using SC processing with the deep window (blue) overlaid with the correct S1 and S2 (red). The scalars are recovered with high accuracy. As a consequence, after the redatuming the strong artifacts that we observe on the Figures 3a are suppressed. For the shallow window SC processing is able to grasp the period of oscillations, but the actual amplitudes diverges from S1 and S2 scalars (Figure 5a and 5b). As a result, after the redatuming we observe a discontinuous reflection arrival (Figure 3e). Moreover, the average NRMS between redatumed surveys reduces to less than 1% for any window size. This means, while imaging may be not as accurate compared to the true amplitudes of the unmodified survey, we can successfully improve repeatability using SC scaling with early arrivals, when this part of the data is more stable and reliable, than reflections.

**Receiver amplitude variations**

Consider now a case when receiver coupling changes or other reasons cause receiver amplitude variations. These variations will not create artifacts on the virtual source gather, because virtual source can be constructed for each pair of receivers independently (Bakulin et al., 2006):

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

Here $\hat{U}(\boldsymbol{x}_B, \boldsymbol{x}_S; t)$ is the full wavefield at the receiver $\boldsymbol{x}_B$, $\hat{U}_{inc}(\boldsymbol{x}'_A, \boldsymbol{x}_S; t)$ is the incident field at the receiver $\boldsymbol{x}'_A$, which is the location of the virtual source. Since stacking is performed over all sources $\boldsymbol{x}_S$, the scalars $\alpha_A$ and $\alpha_B$ that depend on the receiver coordinates can be taken outside of the sum. As a result, the correlation of the wavefields and summation over the sources will not suffer from varying receiver scaling. However, the result of this sum will be multiplied by a scalar $\alpha_A \alpha_B$, which depends on the location of the receiver $\boldsymbol{x}_B$ and virtual source $\boldsymbol{x}'_A$,. Consequently, after redatuming of the data with modified receiver amplitudes the

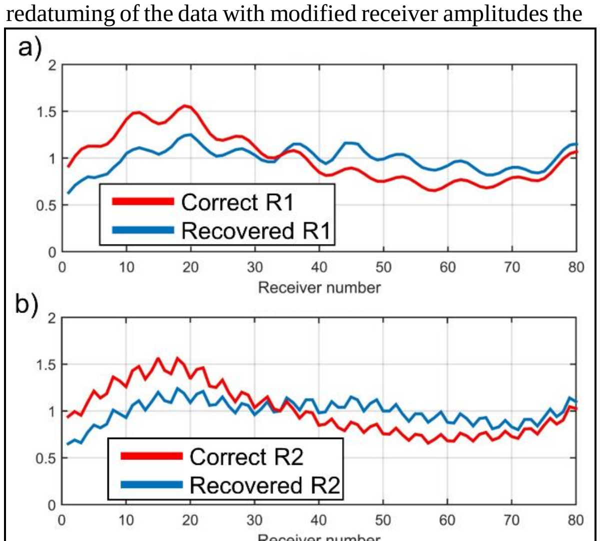


Figure 6: Receiver scalars estimated using SC scaling with a deep time window for the a) monitor survey 3 and b) monitor survey 4.

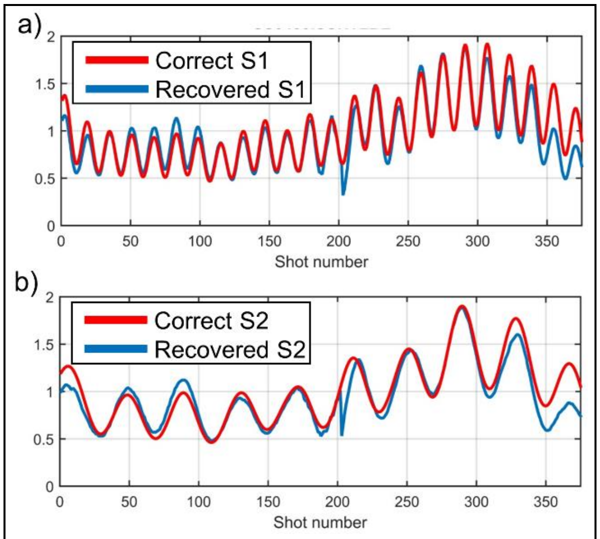


Figure 7: Shot scalars estimated using SC scaling with a deep time window for the a) monitor survey 3 and b) monitor survey 4.

virtual source gather will contain both source and receiver variations:

$$\hat{C}(\boldsymbol{x}_B, \boldsymbol{x}'_A; \omega) = \alpha_A \alpha_B \sum_s \hat{U}\left(\boldsymbol{x}_B, \boldsymbol{x}_S^{(s)}; \omega\right) \hat{U}^*_{inc}\left(\boldsymbol{x}'_A, \boldsymbol{x}_S^{(s)}; \omega\right). \quad (2)$$

The multi-dimensional deconvolution-reconvolution approach does not allow correcting different receiver scaling, because it targets the source signatures. Therefore, there are two options for applying SC scaling:

1) Correct receiver amplitudes before redatuming,
2) Perform redatuming and correct amplitudes of both receivers and virtual sources.

We perform another test where we apply both shot and receiver scalars to the data and try to balance the amplitudes using SC scaling. We denote these surveys as survey 3 and survey 4. Receiver scalars R1 and R2 are presented in Figure 6 (red line), while the source scalars remain the same as in the previous test. Note that we select R1 and R2 so that in both monitor surveys, receiver and source scalars have different oscillation frequencies.

We run SC scaling on each survey separately using a deep time window (800 – 1700 ms). The recovered source scalars (Figure 7) are almost as accurate as in the previous test (Figure 4). The trend of the recovered receiver scalars is not as accurate. However, the oscillation frequency was estimated correctly.

| Variations in: | source amplitudes | | receiver amplitudes | |
|---|---|---|---|---|
| | Image after redatuming | Repeatability after redatuming | Image after redatuming | Repeatability after redatuming |
| **Virtual source** | Artefacts | Low | Source and receiver amplitude variations | Low |
| **MDD + convolution** | Artefacts | High | No improvements | No improvements |
| **MDD + convolution (homogeneous PSF)** | Artefacts suppressed | High | No improvements | No improvements |
| **SC scaling before VS:** | | | | |
| **shallow window** | Artefacts partially suppressed | High | Small improvements | High |
| **deep window** | Artefacts suppressed | High | Some improvements | High |

Table 1: Different workflows and their effects on image and repeatability after the redatuming in case of amplitude variations of sources and receivers.

**Conclusions**

We demonstrated the effects of source and receiver scaling on the image and repeatability of the virtual source gathers and suggested workflows that can reduce or remove these effects. First, we considered source amplitude variations, which induce strong artifacts after the virtual source redatuming. We improved the repeatability using a deconvolution-convolution approach where one of the surveys is used as a reference survey. This method, however, does not remove artifacts but rather make them more repeatable. To improve both image and repeatability we used a modification of this approach, which uses a reference PSF, computed for a homogeneous replacement of the near surface. Alternatively, we can balance the amplitudes using SC scaling. We showed that utilizing a deep time window allows recovering of the shot scalars with high accuracy, meaning that both image and repeatability are improved. In situations where reflection amplitudes are not reliable due to signal-to-noise issues, a shallow time gate can be used. In this case, SC scaling significantly improves repeatability, but does not reduce image artifacts effectively.

Second, we considered receiver amplitude variations. While these variations do not introduce artifacts, they cause amplitude variations of both sources and receivers on the virtual source gather. The multi-dimensional deconvolution-convolution approach cannot address this issue. Therefore, we suggest correcting receiver amplitudes before redatuming or both source and receiver amplitudes after redatuming using SC scaling.

**Acknowledgements**

We thank Saudi Aramco for support and permission to publish.

http://dx.doi.org/10.1190/AM2016-13857811.1



**REFERENCES**

Almutlaq, M. H., and Margrave, G. F., 2013, Surface-consistent matching filters for time-lapse seismic processing: Geophysics, **78**, no. 5, M29–M41, http://dx.doi.org/10.1190/geo2013-0049.1.

Alexandrov, D., Van der Neut, J., Bakulin, A., and Kashtan, B., 2015, Improving the repeatability of the land seismic data using multidimensional deconvolution-convolution approach: 77th Annual International Conference and Exhibition, EAGE, Extended Abstracts, 1–5.

Bakulin, A., and Calvert, R., 2004, Virtual source: new method for imaging and 4D below complex overburden: 74th Annual International Meeting, SEG, Expanded Abstracts, 2477–2480, http://dx.doi.org/10.1190/1.1845233.

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, http://dx.doi.org/10.1190/1.2748490.

Wapenaar, K., and Van der Neut, J., 2010, A representation for Green's function retrieval by multidimensional deconvolution: The Journal of the Acoustical Society of America, **128**, no. 6, EL366–EL371, http://dx.doi.org/10.1121/1.3509797.